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AN OPEN-OCEAN MARINE FOG DEVELOPMENT AND FORECAST MODEL FOR OCE--ETC(U)
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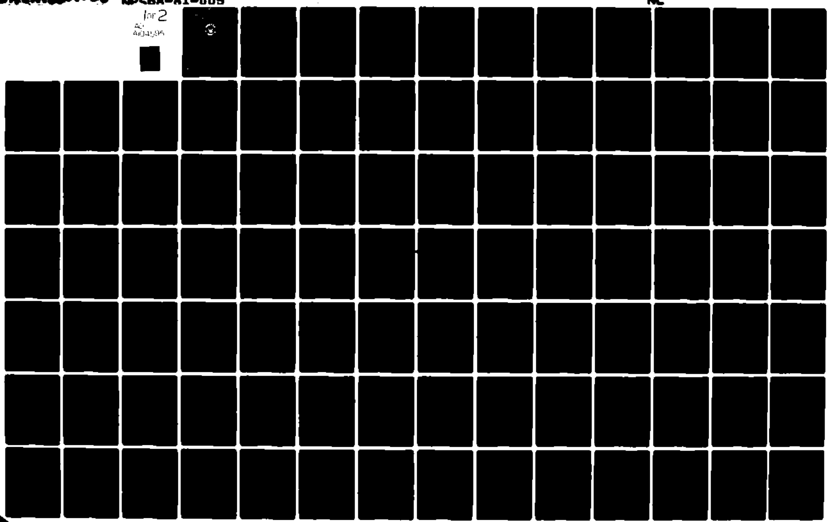

NPS68-81-005

LEVEL II

(2)

NAVAL POSTGRADUATE SCHOOL
Monterey, California

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THESIS

AN OPEN-OCEAN MARINE FOG DEVELOPMENT AND FORECAST MODEL FOR OCEAN WEATHER STATION PAPA

by

Robert Louis Clark

June 1981

Thesis Advisor: G. H. Jung

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Prepared For:
Naval Air Systems Command
Washington, D.C.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: (14) NPS68-81-005
2. GOVT ACCESSION NO.: AD-A104595 (9)
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): (6) An Open-Ocean Marine Fog Development and Forecast Model for Ocean Weather Station Papa.
5. TYPE OF REPORT & PERIOD COVERED: Master's thesis; June 1981
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): (10) Robert Louis Clark (12)
8. CONTRACT OR GRANT NUMBER(s): 131
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Postgraduate School, Monterey, California 93940
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: N6685681WR81003
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Postgraduate School, Monterey, California 93940 (11)
12. REPORT DATE: Jun[redacted]81
13. NUMBER OF PAGES: 129
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Naval Environmental Prediction Research Facility, Monterey, California 93940
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

Advection Fog	North Pacific Ocean Fog	Fog Modeling
Fog Forecasting	Open-ocean Fog	
Marine Fog	Visibility Forecasting	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Marine fog forecasts during the summer period in the North Pacific are not made presently with any acceptable degree of accuracy. Objective fog development models exist and are used with some success for localized coastal regions of the western U.S.; scarcity of accurate data has hindered creation of a reliable open-ocean model. The Eulerian single-station approach, utilizing a segment of the complete accurate data of Ocean Weather Station Papa (50N,145W).

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S/N 0102-014-6601

UNCLASSIFIED 251450

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

#20 - ABSTRACT - (CONTINUED)

is applied in this study to an objective marine fog forecasting model.

The time-series study of significant atmospheric variables at OWS Papa, when coupled with a chronological synoptic overview, delineates accurately fog/no fog sequences in the summer months of 1973 and 1977. Actual observed fog situations are evaluated by the general model and presented in relation to open-ocean fog indices, NOAA 5 satellite coverage and synoptic history.

The open-ocean forecast model is tested on an independent data set for the month of July 1975 at OWS Papa, with favorable results.

The research delineates four required indices that must all be positive to forecast fog. These indices, when plotted daily in the region of OWS Papa allow a single station to predict, with some confidence out to twenty-four hours, the occurrence of advection fog.

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An Open-Ocean Marine Fog Development and Forecast Model for Ocean Weather Station Papa

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
June 1981

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ABSTRACT

Marine fog forecasts during the summer period in the North Pacific are not made presently with any acceptable degree of accuracy. Objective fog development models exist and are used with some success for localized coastal regions of the western U.S.; scarcity of accurate data has hindered creation of a reliable open-ocean model. The Eulerian single-station approach, utilizing a segment of the complete accurate data of Ocean Weather Station Papa (50N,145W) is applied in this study to an objective marine fog forecasting model.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TABLE OF SYMBOLS AND ABBREVIATIONS

C	Degrees Celcius
ft.	foot
Fig.	Figure
G/KG	Grams/Kilogram
GMT	Greenwich Mean Time
HT	Height
I.H.	Inversion Height
Kt	Knots
M	Meters
mb	Millibars
NAS	Naval Air Station
NOAA	National Oceanic and Atmospheric Administration
NPS	Naval Postgraduate School
NM	Nautical Miles
OWS	Ocean Weather Station
PST	Pacific Standard Time
RAOB	Radiosonde Observation
RH	Relative Humidity
SAT	Surface Air Temperature
SST	Sea Surface Temperature
T	Temperature
Z	Zulu Time

ACKNOWLEDGMENTS

The author expresses his sincere appreciation to his thesis advisor, Dr. Glenn H. Jung of the Naval Postgraduate School, for his long hours of professional and patient guidance. His advice and assistance both as a Professor of Oceanography and as a friend were immeasurable.

Deep gratitude is also expressed to Professor Emeritus Dale F. Leipper who provided hours of detailed background, countless articles and constructive and concise comments on the preparation of this paper.

In particular, the author wishes to thank his wife Mac for her loving understanding and encouragement.

I. INTRODUCTION AND BACKGROUND

Marine fog forecasting is one of meteorology's difficult remaining problems. Although the individual major variables affecting fog formation are well known, the great variability of factors involved such as cloud cover, wind, radiation, temperature, surface currents and synoptic weather features serve to make the forecast problem quite complex. Compounding difficulties in research on fog formation, marine meteorological sampling stations are scarce; also reports from ships of opportunity are seldom made by trained meteorological observers and are lacking in the accuracy necessary for a forecast model (Schrock and Jung, 1976).

For the purposes of this study, marine fog was defined as listed in the Federal Meteorological Handbook, No. 2 (1969):

> fog - a visible aggregate of minute water particles based at the earth's surface which reduces horizontal visibility below 1,000 meters (5/8 mile).

This reduction in visibility by water vapor corresponds to code figures 90 to 94 as described in this reference (Appendix A).

When fog occurs and extends downward to the ocean surface, its impact is substantial on both commercial and military activities. Effects and restrictions on naval operations have been accurately delineated (Wheeler and Leipper, 1974); more recently, specific aircraft carrier operational situations

in relation to restricted visibility have been described (Selsor, 1980).

Historically, the approach to the problem of accurate fog forecasting has been varied. Thorough knowledge of the present synoptic condition is a prerequisite for a future prediction. Misciasci (1974) listed three main categories of analytical fog research: (1) climatological, (2) synoptic, and (3) statistical-numerical. To describe more fully all branches of fog research, Schrock and Jung (1976) expanded the number of research categories to six: (1) microphysics and physics of fog formation and dissipation, (2) statistical-numerical modeling and forecasting, (3) depiction of fog areas over the open ocean from satellite information, (4) marine fog climatology, (5) synoptic modeling and forecasting, and (6) classificational descriptive definitions. The research in this first approach utilized the synoptic modeling and forecasting method to establish offshore conditions for one specific coastal fog study.

A second approach that has shown some success in marine forecasting is the statistical-numerical modeling and forecasting category. Utilizing a statistical regression analysis with a limited set of numerical model output parameters (MOP's), work was initiated at the Naval Postgraduate School (NPS), Monterey, California starting with Schramm (1966) and further refined by Nelson (1972), Aldinger (1979), Yavorsky and Renard (1980), and Selsor (1980). The final model output

statistics (MOS) three-category scheme (Selsor, 1980) is an operationally-oriented method, yet the data input for the necessary coverage and accuracy remains lacking.

A third approach, which is the focus of the present research, utilizes a very localized time series of significant atmospheric variables as a fog development model in conjunction with a large scale synoptic overview to provide the forecast basis. This approach and objectives are described in the next chapter.

II. APPROACH AND OBJECTIVES

Global fog forecasting and, more specifically, the ability to forecast timing and extent of marine fog is still in its early stages. Only the United States Navy's Fleet Numerical Oceanography Center has an operational objective fog forecast program. It is based on a computerized statistical analysis of five weighted fog-related model output parameters which are products of numerical analysis or primitive equation models.

According to Renard (1976) there still exist two major problems that are symptomatic of inaccurate marine fog forecasts:

1. Initial-state depiction of marine fog is incomplete and inaccurate.
2. Currently available climatological marine-fog statistics are contradictory and/or inaccurate.

A major objective of the present research is to reduce the first of these stated problems by providing, for one location, an accurate and complete history of fog related variables. This is accomplished by utilization of a single station of professionally-recorded data. Although this is a little-used approach to the forecasting of marine fog, the time-series method itself is not historically new.

The use of a synoptic approach to predict fog formation, coupled with a day-to-day sequence focusing on a localized area, was first described in Leipper's (1948) classic paper,

"Fog Development at San Diego." This systematic approach was successful once the effects of local influences were understood as to their impact on a set of initial atmospheric conditions. This material was reviewed and the area of application extended to the Santa Monica area in a subsequent article by Leipper (1968).

Since that time there have been several recent coastal studies, such as McConnell (1975), Peterson and Leipper (1975), Schrock and Jung (1976), Beardsley and Leipper (1976), and Evermann and Leipper (1976), that have applied Leipper's model to specific localized coastal regions of the eastern Pacific. The success of these studies at limited coastal locations and the proposed synoptic marine fog model patterned by Evermann suggested the possibility of adapting a working coastal fog development model to the open ocean situation.

The overall objective of this study is to attempt to adapt a successful coastal fog development model to a completely marine format. In this case the location chosen at which to develop the model is in the Northeast Pacific, specifically the Gulf of Alaska region. The research applies an Eulerian single-station approach utilizing the complete and accurate data record of Ocean Weather Station Papa (50N, 145W) in the central Gulf of Alaska (Figure 1). The reasoning behind using the Eulerian single-station approach with a time-series study of atmospheric variables is the representative location of Ocean Weather Station Papa with respect to an open

ocean location for fog application and the completeness and accuracy of the data record.

Canadian operation of Ocean Weather Station Papa began in December 1950. The station has since been used primarily to make meteorological observations of surface and upper air variables and to provide an open ocean air-sea rescue service. The station itself, located in time zone plus ten west, is manned by two vessels operated by the Marine Services Branch of the Ministry of Transport (CCGS Vancouver, CCGS Quadra). Each vessel spends six weeks on station in rotation before returning to the mainland. Weather observations are made and recorded by trained weather observers.

A prerequisite to accurate fog forecasting is the detailed knowledge of the present mesoscale features of the lower atmosphere as well as a knowledge of the general synoptic state and recent history. The Leipper coastal forecasting approach centers around the atmospheric vertical temperature structure of the lower three thousand meters (below 900 mb). Leipper's model is a four-stage series that was extended northward to the central California coast where Peterson and Leipper (1975) adapted it to a three-stage model.

In general, the first stage is initiated when the North Pacific subtropical high moves eastward to an inland position over northern California. Subsidence causes the continental air to be warm and dry and this factor is further enhanced by a downslope and offshore flow with adiabatic warming. The flow of warm air over the cooler coastal water initiates a

low-level surface inversion. This inversion restricts vertical movement and confines any increase in the moisture content to the layer adjacent to the sea surface. With the air mass above the inversion relatively dry, there is increased radiational cooling. Stage two is indicated by a decrease in the offshore flow so that the offshore air mass is relatively stationary over the colder ocean surface. A surface inversion is formed and the surface layer becomes nearly saturated at a temperature very close to that of the underlying sea surface. Stage three is the return of the normal northwesterly flow and advection of the now nearly saturated air mass with a further trajectory over the cold upwelled water. Due to the effects of radiational cooling from the top of the layer, cooling from below by the sea surface, and mixing within the layer, saturation occurs and fog forms. Once formed, the fog layer cools by radiation from the top of the cloud layer to a temperature several degrees below that of the sea surface. There are two effects that serve to intensify and maintain the fog. There is a flux of heat and moisture upward at the sea surface. The lapse rate is super-adiabatic because of radiational cooling from above combined with the heating from below. Secondly, since the layer remains cooler than the sea surface temperature, the evaporative process can continue as the evaporation is governed by the sea surface vapor pressure gradient. Stage four occurs as the layer deepens to four-hundred feet or more. The onshore winds and convective instability due to radiational cooling serve to increase this

layer depth. In the layer-deepening process, a point is reached where the depth of the fog layer below the inversion is such (1300 feet at San Diego) that radiational cooling can no longer increase the cloud depth. It then becomes a stratus regime with the saturated layer lifting off the surface. The entire process usually evolves through a period of approximately five days, according to Leipper (1948).

After the general development scheme was explained, Leipper analyzed several fog-related variables and defined three non-diurnal indices based on these parameters that provide a necessary condition for the formation of fog at San Diego. Appendix C is a worksheet taken from the Naval Weather Service Facility Local Area Forecasters Handbook for San Diego, California, that utilizes the Leipper variables as well as indices for making a fog forecast. This objective fog forecasting method is presently in use at NAS Imperial Beach, NAS North Island, and NAS Miramar, all located in the San Diego area.

The variables presently used in the Leipper method are as follows:

1. The base of the inversion of the 1200Z Montgomery Field (San Diego, Ca.) upper air sounding.
2. The highest air temperature above the base of the inversion, if an inversion exists with a base below 3000 feet.
3. The sea surface temperature at 0800 Pacific Standard Time (PST) taken at Scripps Pier (La Jolla, Ca.).
4. The dew point temperature taken at Lindbergh Field (San Diego, Ca.) at 1700 PST on the preceding day.

These variables are combined to form three indices that all must be favorable on a given day to forecast fog assuming

little moisture in the upper air. The period of observation or "fog day" was defined as the period from 1630PST on one calendar day through 1629PST the following day. These indices are listed below:

1. Height of the Inversion Base; to be favorable, the height of the inversion base must be less than 1300 feet [Variable (1) above].

2. Temperature Index; if an inversion exists with a base below 3000 feet, the temperature index is the highest temperature above the inversion base minus the sea surface temperature [Variable (2) minus (3) above]. Surface air temperature is substituted for the highest temperature above the inversion base if no inversion exists with a base below 3000 feet. To be favorable, the quantity must be greater than or equal to zero degrees C.

3. Moisture Index; this index is defined as the difference between the dew point temperature and the sea surface temperature [Variable (4) minus (3) above]. A favorable value is any positive value or any negative value between zero and minus five degrees C.

The earliest time-series approach to fog forecasting in an open ocean environment was Leipper's (1945) Forecasting Summer Fog at Shemya which also suggested application to other northern Pacific areas. Ogata and Tamura (1955) conducted a sea (advection) fog study at Ocean Weather Station Extra (39N, 153E) that was a continuous time-series examination of synoptic conditions. Grisham (1973) utilized synoptic ship reports in compiling a statistical fog comparison that indicated a positive relationship between the occurrence of marine advection fog and the temperature and moisture index approach. A study by Misciasci (1974) was similarly conducted at Ocean Weather Stations Sierra (48N, 162E) and Quebec (43N,

167W). Misciasci's results indicated that there was indeed a possibility of extending a coastal type fog development model to the open ocean. For example, the analysis showed that although the temperature index did not appear to give a good indication of fog and non-fog situations, the moisture index did have a positive correlation. Also noted was a relation between layer thickness and fog duration as well as little diurnal dependence shown by the variables.

An approach to fog forecasting on the West Coast using some concepts and some questions was described in a working paper by Leipper (1976). A similar approach to offshore forecasting was presented by the Calspan Corporation (Rogers, 1981). Since 1972, the Calspan Corporation, in conjunction with the Naval Postgraduate School (NPS), has been investigating marine fog formation offshore along the western coast of the United States. Although the research was initially directed at the microphysics of the fog problem, their recent applications have been in relating micro- and meso-scale processes to synoptic-scale events to propose an experimental "decision tree" for use in conceptual forecasting of coastal (marine) fog (Rogers, 1981). Their research distinguishes between at least four different types of offshore west coast (marine) fog (Pilie, 1979):

1. Fog triggered by instability and mixing over warm water patches.

2. Fog developed as a result of lower (thickening) stratus clouds.

3. Fog associated with low-level mesoscale convergence.

4. Coastal radiation fog advected to sea via nocturnal land breezes.

Of special note are the results concerning temperature. Once fog had formed, their results support the observation that air temperature within the fog is not dominated by the ocean temperature and the air temperature exiting downwind from the fog patch was some 0.5 degrees (C) cooler than the air entering the upwind fog edge, inferring an on-going process of long-wave radiational cooling within the patch.

In view of the many previously-cited positive indications of a consistent fog process existing between the marine coastal regime and the open ocean, the present research set an objective of modifying a working coastal model based on variables and indices presently in use to the open ocean regime of Ocean Weather Station Papa.

The research approach, in shifting the analysis to an open ocean format, expects several factors specifically to change. Upwelling and diurnal effects will not be as strong as observed near coastlines and the surface radiational heating, seen as a dissipating mechanism, will no longer be a critical factor. Advection strength, duration and trajectory should become factors that will replace at sea the adiabatic downslope air flow stage of the Leipper coastal model.

The Eulerian single-station approach utilizing time-series studies at OWS Papa will examine data acquired in the months of July and August for the years of 1973 and 1977. These

months are most representative of the summer fog regime based on climatology for the North Pacific Ocean. The developmental fog model, based on adapted and modified indices, will be then compared to an independent data set for a specific period during an additional year at the same station. The data base is examined in the next chapter.

III. DATA

All data for the present research were originally recorded at Ocean Station Papa, and they were obtained through the Naval Weather Service Detachment at the National Climatological Center, Asheville, North Carolina (Appendix B). Additionally, the satellite coverage for these two years (1973 and 1977), although first recorded at Elmendorf A.F.B. Alaska, was received from the satellite archives at the University of Wisconsin, Madison.

Figures 8 through 27 are the record of pertinent data (variables) for this research. For each of the four months examined, the following time series figures are presented every twelve hours at 00Z and 12Z: (1) Wind direction in degrees, (2) Wind speed in knots, (3) Air temperature, dew point temperature and sea surface temperature, all in degrees C, and (4) Sea level pressure in millibars. The inversion height in millibars is taken from the plot of the daily 00Z RAOB. If an inversion does not exist it is specifically noted on the time series plot. A key figure is the recorded horizontal visibility which is plotted using a range code. Appendix A is a listing of this code in nautical miles along with a corresponding World Meteorological Organization equivalent in kilometers. For this study, fog is represented by the codes 94 through 90. The time series figures show the fog blocks labeled 94 and less than or equal to 93. As

described in Chapter I, any visibility less than 5/8 mile (1000 meters, or the 94 category or less) is considered open ocean fog. Additional variables analyzed in time series graphical form but not reproduced in this report are:

1. maximum temperature of the sounding;
2. air temperature minus dew point temperature;
3. dew point temperature minus sea surface temperature;
4. air temperature minus sea surface temperature;
5. station reports of fog (all visibility codes less than or equal to 98).

These figures are omitted since the specific form of the first four figures did not contribute significantly to the open ocean fog development indices, presented in detail in Chapter IV, as being critical to a successful forecast model. The fifth figure was omitted because the reported range of fog codes was much broader than the focus of this study.

In the 124-day period of the analysis, there were eighteen specific cases of open ocean fog lasting twelve hours or more that fit the study category of restricted visibility; i.e., visibility less than or equal to 5/8 statute miles. Ten of the cases were associated with synoptic frontal activity while eight were non-frontal in origin and maintenance. The months of July 1973 and July 1977 each had two occurrences of fog, one being frontal and the other non-frontal. August 1973 and August 1977 had the majority of the fog occurrences; August of 1973 had seven (four frontal in nature and three non-frontal), and August of 1977 had seven (four frontal and

three non-frontal). Of the entire four-month period, there were nine days of data missing from the record so that a 115-day record is used for the percentage calculations. For example, there were 468 hours of "fog case" periods, as compared to the 2760 total hours (115 days), resulting in a 16.9 percent rate of fog for the period.

The station reports of Ocean Weather Station Papa indicate a much higher incidence rate of fog. For the same period, station reports listed some twenty-four cases of fog versus the eighteen of this study. Fog was reported present for some 660 hours (versus the 468 hours of this study), resulting in an occurrence rate of 23.9 percent. This greater amount of station-reported fog is due to the reporting procedure that includes the "light fog" cases of restricted visibility codes of 98 through 95 in addition to the codes (94-90) used in this study as the defined cutoff for the presence of fog.

These frequency rates, 16.9 percent for codes 90 through 94 and 23.9 percent for codes 90 through 98, compare most favorably with computer-assisted climatological marine fog frequencies for the eastern North Pacific Ocean. Ocean Weather Station Papa, for the years 1963-1974, has a climatological fog frequency of nearly 20 percent for the codes 90 through 96 (Renard, 1975).

Although the variables and indices developed for the non-frontal open ocean fog appear to be related to frontal fog as well, the forecasting of frontal fog is not addressed by

this study for two major reasons. First, frontal fog as compared to the non-frontal case is much shorter in duration. In the four-month period examined in this study, nine of the ten cases of frontal fog were recorded as persisting for only the shortest duration interval (12 hours), whereas in the eight non-frontal cases the average duration was for thirty-nine hours. Although ideal for a further study, the overall economic and strategic impact of the frontal fog is reduced because of its shorter duration. Secondly, since the frontal fog initiation time is tied directly to the large-scale synoptic frontal feature, it is much more easily forecast than the non-frontal case. Frontal movement is now routinely and accurately observed at sea through satellite coverage, with the direction of movement and speed well defined by loop analysis.

Appendix E presents the chronological series of vertical temperature soundings plotted from the surface to the 500-millibar level on skew T-log p coordinates. Independent soundings taken at 00Z daily exist for 108 days of the 124-day study periods at OWS Papa.

In the following chapter, these parameters are combined with adjustments to the Leipper coastal model indices to provide an objective open-ocean fog model. The synoptic framework is integrated with the fog development model then to provide the forecast criteria.

IV. FOG DEVELOPMENT MODEL AND OPEN OCEAN INDICES

There are eight periods of non-frontal fog in the months covered by this study. Although lasting an average of thirty-nine hours, the fog sequences cover durations of twelve to one-hundred eight hours.

As previously described, the Leipper coastal model is based on a four-stage development. In subsequent studies, Peterson (1975) and Evermann (1976) present coastal models of three and five stages respectively. A key relationship between these three development models of coastal fog is the similarity of chronological physical development. The general development model is an idealized chronology of evolution focusing on key physical steps which, combined, comprise a typical physical sequence. In nature, the sequence may be retarded, accelerated, interrupted, etc., by fluctuations of the larger scale circulation.

The eight widely-varying periods of non-frontal fog in this study are each seen as at least a portion of a single idealized development model. Stage I of the open ocean model occurs with the positioning of the mid-Pacific subtropical high in a location generally to the southeast of the forecasting station, OWS Papa (Fig. 2), so that the station falls under the synoptic influence of the high. The surface sea level pressure at OWS Papa begins to rise as the high pressure system intensifies and increases in magnitude under the influence of

the long wave ridge. In seven of the eight fog sequences (Table III) this rise in pressure is the initiating feature. In one case (Case 2) a major low pressure system is located just to the south of the recording station, and it will be treated as an anomalous case. Its development, though having very similar variables and indices, is not the subsidence/ advection sequence that seems to be typical for this area.

Table I shows that in each of the eight cases, the period of occurrence of fog is preceded by a steady increase in the surface pressure. The period of intensification was found to last from twelve hours to as long as five days with an average period of intensification lasting some two and a half days (1.12 day standard deviation). The pressure increase during this intensification period averaged 4.6 millibars (3.13 mb standard deviation) per day and it is the first indication of a subsidence-dominated regime that contributes to the fog formation at OWS Papa. Close analysis of the daily RAOB history (Appendix E) further confirms subsidence prevailing over the station in this initiating stage. The subsidence effectively creates a near-surface layer with a warm, relatively dry upper air mass overlying a shallow cooler and more moist marine layer.

A second major definitive factor in Stage I in each of the eight cases, is a steady increase in the dew point temperature prior to the formation of the open ocean fog. The average period of rising dew point temperature was 2.2 days

(0.82 day standard deviation), very nearly the period of the sea level rise in pressure (2.5 days). The magnitude of increase in dew point temperature ranged from 1.5°C to 5.5°C for specific periods (Table II) and the average rate was a 1.5°C rise per day with a standard deviation of 0.67°C. There was a steady increase in the water content per unit volume of the marine layer, indicated by this rise in dew point temperature. This is a result of advection taking place simultaneously with the subsidence noted earlier.

In all seven cases examined in this model (Case 2 omitted) there was a relatively long uninterrupted flow of low level air from the south due to the circulation on the western side of a high pressure system that dominates the recording station. Recorded wind directions ranged from 120°T to 290°T for the seven cases depending on the exact orientation of the high pressure system in relation to OWS Papa. Additionally, the wind speeds remained relatively steady (3 to 15 knots), prior to the formation of fog.

Due to the station variables' dependence on orientation relative to the position of the subtropical high and the magnitude of the winds, this open ocean non-frontal fog is termed an advection fog. In the advection process, the surface air mass is advected northward. In the overlying air mass, measurements indicate a temperature higher than that of the air initially over OWS Papa at the outset of Stage I. Thus, the air temperature is seen to rise prior to the onset

of fog for each of the cases. Additionally, in each of the eight cases the low layer of marine air is found to be warmer than the sea surface in Stage I as well as during all or part of the period that fog was actually present. Thus in the advection process, there is cooling of the air mass from below by the sea surface as well as turbulent mixing due to the low level winds. These factors, in conjunction with the subsidence-induced layer capping the low level air mass, serve to modify the trapped marine layer and to lead towards saturation.

Stage II is initiated at saturation with the advection fog forming as a very shallow layer with the inversion very near the surface. Over the average duration (39 hours) of fog present at the recording station, the surface layer thickened slightly as the measured inversion height increased although not one of the eight cases examined in the study had inversion heights that were recorded over 1000 feet during the period that fog was present. The mechanism for maintenance and thickening of the fog in this stage appears to be radiational cooling from the top of the layer as well as cooling from below by the sea surface. Throughout this stage, winds remain steady in magnitude, averaging nearly 10 knots, and direction. The rise in dew point temperature and surface pressure, measured prior to the saturation stage, ceases during Stage II.

Stage III commences with the dissipation of the existing fog. In each of the cases, dissipation was due to frontal

effects. Within six to twenty-four hours after the recorded end of the fog periods, there was a passage of either a cold or occluded front over the OWS Papa area. The average period of time between fog termination and frontal passage was 13.5 hours. Tables I and II show the rates of decrease for sea surface pressure and dew point temperature that accompany the dissipation stage for each fog case. The sea surface pressure decreased for an average of 1.6 days (0.49 day standard deviation) in the post-fog stage at an average rate of 5.2 millibars per day (2.0 mb standard deviation). This decrease is very consistent with the frontal passage initiating the fog dissipation. The dew point temperature decreased over an average period of 1.7 days (standard deviation of 0.99) at an average rate of 1.9°C per day (1.67°C standard deviation). This is very consistent with the 1.6 day average period of pressure decrease. The dew point temperature decrease is a direct result of the post-frontal clearing and decrease in humidity.

The post-frontal period also was indicated by a decrease in the air temperature and either an elevated (above 3000 feet) or non-existent inversion. An analysis of the daily synoptic charts for this stage showed a decrease in the intensity and magnitude of the sub-tropical high. In decreasing in magnitude, the high pressure system's influence retreated in a southeastward direction away from OWS Papa as the short wave trough and associated frontal activity moved

over the recording station area. The entire three-stage process lasted an average of some six days.

With the open ocean fog development model described, the Leipper coastal fog model variables and indices were examined in an attempt to modify them based on the development model so that an accurate set of forecast indices would be established for the open ocean case. The variables which are recommended for use in the open ocean forecast model are as follows (all data recorded at OWS Papa):

1. The base of the inversion (in mb) as recorded from the 00Z RAOB.

2. The highest air temperature above the base of the inversion if an inversion exists with a base below 3000 feet, measured at 00Z in °C.

3. The sea surface temperature measured at 00Z and 12Z in °C.

4. The dew point temperature measured at 00Z and 12Z in °C.

5. The surface wind direction in degrees true and wind speed in knots at 00Z and 12Z.

These five parameters, when combined as described below, form four indices that all must be favorable on a given day to forecast fog. The period of observation is defined as from 1400 local (00Z) the preceding day through 1400 local the recording day with the forecast valid for the next twenty-four hours. The open ocean fog forecast indices (Appendix D) are:

1. Height of the inversion base: to be favorable the height of the inversion base at 00Z must be less than 1000 feet.

2. Temperature index: the temperature index is the highest temperature above the inversion base at 00Z minus the sea surface temperature (00Z) recorded the previous day. To be favorable the quantity must be greater than or equal to 0°C.

3. Moisture index: the moisture index is the dew point temperature (00Z) minus the sea surface temperature (00Z) recorded the previous day. To be favorable the quantity must be greater than or equal to a negative 0.5°C.

4. Advection index: the advection index is a combination of the wind direction and wind speed at 00Z. To be favorable the winds must be between 120°T and 290°T and greater than three knots but not greater than 15 knots.

Index accuracy for the advection fog periods of this study is excellent. The inversion height index and advection index were favorable for each of the 276 hours of fog present (Table III) in cases developing past Stage I of the model. The temperature index was favorable for all but twelve of the fog hours or was correct more than 95 percent of the time. The moisture index was correct (favorable) all but 48 hours of the advection fog periods or more than 82 percent of the time. When combined into the forecast model, the indices correctly indicated the presence of every fog case and were completely favorable for over 78 percent of the total durations of the fog periods.

The indices not only successfully delineated the presence of fog, but were successful in indicating the initiation and cessation of fog periods or the limits between Stages I and II and Stages II and III of the development model as well. In every case, at least one index was unfavorable in the

24-hour period prior to the formation of fog, and, in every case but one, at least one index was unfavorable in the first twenty-four hour post-fog stage (Table IV). Since only one index is needed to indicate a no-fog case, the open ocean indices had an overall success rate of 93 percent of delineating the no-fog periods of Stages I and III as well as the success in indicating the Stage II fog presence.

The major modifications made to the Leipper coastal model are summarized:

a. Favorable inversion height is 1000 feet in this open ocean model, down from the 1300 feet of the coastal model.

b. The timing of recording observations for the open ocean model is uniformly 00Z and all readings are made at OWS Papa.

c. Winds are a factor in the open ocean case as the fog is of the advection type.

d. The temperature depression between dew point temperature and sea surface temperature is only -0.5°C instead of the full -5.0°C of the coastal model. This is likely due to the fact that, in the open ocean case, the surface layer is always in contact with the sea surface and is relatively moist at all times. The large temperature depression of the coastal and inland regions is not observed.

A single case of open ocean fog is now presented in relation to the theoretical development model. Figures 3 through 7 support this analysis as they are the chronological synoptic history covering the three stages of development for fog Case 6 (Figures 23-27, and Tables I-IV). At 00Z on 10 August 1977, the synoptic overview shows that the subtropical high is relatively weak (1020 mb) and is pressed up against the North American continent. Dominating the OWS Papa region, in

fact dominating the entire eastern North Pacific, is a large, intense low pressure system (996 mb). Although the period of fog initiation was 48 hours away, there is already an upward trend in the dew point temperature that began at 00Z 09 August. The development model stage I begins at 00Z 10 August as the rising dew point temperature couples with a rising sea surface pressure when the subtropical high begins an intensification process and the low pressure system to the west of the station begins to dissipate. Over the next 48 hours prior to fog formation, the sea surface pressure over the recording station will intensify some 22 millibars. By 00Z 11 August, the synoptic overview shows the low has decreased in intensity some 6 millibars and has split into two closed circulations. The high has intensified and grown greatly in magnitude. The recording station is now experiencing a long, low-level air flow northward. By 12Z 11 August a steady sea level air temperature rise is noted at the station as the advection process is initiated, moving a warmer air mass northward. At 00Z 12 August, the high center has moved well northward and has intensified just to the east of the recording station. The rapid strong intensification of the high pressure system with the associated strong subsidence has caused the inversion height to move down to less than 400 feet above the ocean's surface by the beginning of Stage II at 00Z 12 August. At this point of saturation, the fog forms and lasts for a 48-hour duration. Sea surface pressure, dew point temperature and air temperature all have

reached their maximum values by 00Z 13 August and have begun to decrease. By 12Z 13 August the fog has ceased since a cold front associated with the low center located in the Aleutian Islands is in close proximity to the west. The low-level inversion of Stage II became an unfavorable index as it rose to an elevation of over 2500 feet due to the frontal effect. The decrease in dew point temperature, air temperature, and sea surface pressure continued through Stage III; the decrease in dew point temperature lasting 48 hours after Stage II was over. The 00Z 14 August synoptic overview shows the subtropical high dissipating in magnitude to the east of the recording station as the cold front has passed and the low pressure to the west has intensified. By this time, the moisture index had become unfavorable. By 12Z 14 August, the wind index and temperature index had become unfavorable and the 00Z sounding on 15 August showed the inversion height unfavorable.

The entire sequence of the three stages of development for this case 6 lasted some five days. The open ocean model accurately fits this example case and the fog sequence has been accurately delineated by the open ocean indices. Additionally, pre-fog and post-fog variable tendencies correctly indicated formation and dissipation.

Analysis of DMSP satellite coverage for this specific case 6 effectively complemented but was not essential in the open ocean forecast method developed. NOAA-5 visible and IR

coverage on 9, 11, 12, and 15 August 1977 was examined for the Gulf of Alaska area. The IR coverage on 9 August is dominated by the intense low pressure system over the Northwest Pacific. The IR coverage on 11 August definitely showed the intensification of the subtropical high in the eastern Gulf by a widespread area of clearing. The low pressure to the west of the OWS Papa is much reduced in size and patches of low level stratus (possibly fog) are seen in areas near the recording station. Satellite coverage similar to that on this specific day may have excellent future use in delineating fog patch extent as the low level stratus is bordered by large clear areas in the anticyclonic regime. The IR satellite coverage on 15 August nicely showed the cold front activity that had earlier caused the dissipation of the advection fog at OWS Papa. Although there are problems in interpreting differences between low-level stratus and surface fog, satellite support of the open ocean fog development model does effectively delineate fog patch size associated with the high pressure system. Additionally, frontal activity is accurately located via satellite data, thus cessation times of the fog periods may be more accurately predicted since all cases of advection fog in this study were dissipated by frontal activity.

Satellite coverage for Case 7, a 108-hour period of fog during the month of August 1977, was examined. Infrared coverage on 15 August, some twenty four hours prior to the fog initiation, indicated that OWS Papa was in a clear area

with high level clouds to the west and widespread low level stratus to the south. Towards the east and the center of the high pressure system, there was general clearing, while to the north of the station was another large stratus patch extending nearly to the southern Alaska coast. A 20 August visible satellite photo during the latter part of the fog period indicated that OWS Papa was obscured by cloud cover. Because it was a visible satellite photo, cloud height and type were less easily discernible. Clear patches were clearly identifiable on the visible photos, thus maximum possible fog patch size was accurately delineated. A large clear area was present north of OWS Papa towards the center of the high pressure system. There appeared to be an extensive coastal fog bank present in the Gulf, just south of the eastern portion of Alaska. Again, the patch size is accurately shown on the satellite display by the presence of no-cloud areas surrounding the cloud mass. The high pressure circulation itself is well defined and the curvature of flow is easily seen in the cloud pattern. To the west of the recording station, a major frontal band extends in a north-south direction as the low pressure system to the west intensifies. The leading edge of the front is shown by the change from an open cellular regime to that of the high cirrus bands of the front. Frontal width is additionally quite visible. On 21 August the infrared coverage is seen some twelve hours after the dissipation of fog at OWS Papa. The coverage clearly shows the front in

close proximity directly to the west of the station. Frontal activity and frontal width are defined by the high clouds seen in the IR image. Low level clouds, possibly a stratus or fog deck, are seen to the east of the recording station, and they remain widespread, extending eastward nearly to the continental border. The satellite coverage investigated served to enhance the synoptic display as well as the open-ocean fog development model in this case as well. While the satellite data were not critical for the forecast indices, they did serve to show the possible extent of known fog patches as well as specifically delineating non-fog areas.

An independent data set for the month of July 1975 will be examined in the next chapter. The open ocean variables and indices as well as noted trends in the 1973 and 1977 years will be analyzed and the accuracy of the method itself determined.

V. INDEPENDENT TEST

The open-ocean development model was tested on an independent data set. The Ocean Weather Station Papa meteorological records for the month of July 1975 were chosen. The significant atmospheric variables were plotted along with the fog indices (Figures 28-32). Prior to analysis of the observed horizontal visibilities, the indices were examined according to the forecast method (Appendix D) to determine periods of a favorable fog forecast. The forecast periods determined from the indices were then compared to the periods of observed advection fog.

On three occasions, all of the indices were favorable in the forecast model, and, on two occasions, all of the indices were favorable except for the wind direction of the advection index. For the July 1975 period, there were five periods of observed advection fog that correlated in timing and duration with the favorable periods predicted by the open-ocean forecast model.

For the month of July 1975, there were a total of nine fog cases, four frontal and five of the advection type. The seven-hundred forty-four-hour observation period had restricted visibilities for one-hundred thirty two hours or 17.7% of the total recording period. This percentage is consistent with the fog development data for 1973 and 1977 (16.9%) as well as climatology (20%).

Stage II or the fog formation times of the five advection cases are listed:

1. Case I - 12Z July 1
2. Case II - 12Z July 2
3. Case III - 00Z July 8
4. Case IV - 12Z July 9
5. Case V - 00Z July 15.

As noted in the fog development model analysis, the trends for an increase in the dew point temperature prior to advection fog formation and decrease after the fog period were consistent for four of the five independent advection fog cases. Similarly, the trend for a decrease in sea level pressure in the post-fog Stage III was consistent for all five of the advection fog cases. Least consistent with the fog development model was the trend for an increase in the sea level pressure during Stage I of the fog development model. In three of the five cases there was an increase in the sea level pressure immediately prior to fog formation, while in the other two cases, OWS Papa was already in a high-pressure-dominated regime at the outset of Stage I.

The test on the independent data set verified not only the open-ocean forecast method but the three-stage fog development model as well. Detailed analysis of the synoptic reports at six-hour intervals for this time period indicated a similar development scheme and dissipation process by frontal activity.

If the wind direction part of the advection index were expanded sixty five degrees (from 290 to 355 °T), the forecast model would have accurately predicted each of the five

advection fog cases. Without the index corrected, the prediction accuracy was 66.7% or correct for 48 of the 72 hours of advection fog. Further studies may expand the limits for this part of the advection index to better account for flow in the northeast quadrant of the subtropical anticyclone that is consistent with the first two stages of the open-ocean development model.

As well as accurately delineating the actual advection fog periods of the independent test case, the pre-fog period (Stage I) and the post-fog period (Stage III) were correctly delineated in all cases by at least one unfavorable index within the twenty-four hour period immediately prior to fog formation and within the first twenty-four hour period immediately after fog dissipation. This result implies the actual physical mechanics of the fog stages were well represented in the chosen indices.

Although the size of the independent data set was relatively small (25% of the development model data set), consistent fog frequencies with earlier work serve to substantiate and support the positive nature of the results for a single station forecast model. Extensive further testing of the forecast model and related indices at Ocean Weather Station Papa will serve to increase the accuracy of the existing indices, such as modification in the advection index as more fog cases are subjected to the model. Application of the development model and forecast method to data of other professionally

recorded stations in the North Pacific region will serve to test the applicability of this research approach and consistency of this atmospheric event in the open-ocean.

VI. CONCLUSIONS AND RECOMMENDATIONS

The accurate forecasting of open-ocean fog is of vital concern to any ocean-going operation. This study has made a strong step in the direction of delineating accurate fog occurrence for the summer months at OWS Papa based on atmospheric variables and significant fog-identifying indices. The success of the Eulerian single station approach using this objective forecast model, when coupled with a synoptic overview and satellite coverages, presents a most accurate analysis of the fog situation at the recording station. The successful coastal fog model was indeed adaptable to the open-ocean case although several different physical mechanisms were found to be at work, most notably the dissipation caused by passage of cold fronts.

There are specific recommendations applying to this approach. By further extending this successful model to other stations of professionally-measured marine stations, an evaluation can be made as to the applicability of this model and to the consistency of processes at work in the open ocean. These further studies would serve to correlate as well as to refine the presently-developed variables and indices.

At Ocean Weather Station Papa, this model should be further tested and refined with data from additional years. Specifically the indices should be continually examined and smoothed. The moisture index, with further research and adaption of its

measured temperature depression, should become more accurate than the present 82%.

Although this model was developed for the high fog frequency summer months, further research could be directed toward the development of an all-season model.

Frontal fog was not included in this study as it was of short duration (90% of the cases 12 hours or less). However it did occur at a higher frequency, thus there is a need for research in this area. A first look at data in these frontal fog periods shows many strong correlations with the non-frontal cases. The moisture index was consistent and also quite accurate. The advection index, as well as the influence of subsidence on inversion height, did not play a major role in the frontal fog cases.

Examination of specific segments of the fog development model, such as the subsidence mechanism and magnitude within intensifying subtropical anticyclones, would certainly contribute to the accuracy and understanding of the processes in the first stage of the open-ocean model.

Research into the microphysics of the problem is a prerequisite to the complete physical understanding of the processes interacting in the fog formation and dissipation steps. Early work by Businger (1973) and Wyngaard (1973) on turbulent transfer and turbulence over land areas in the atmospheric surface layer have been extended to the "over ocean" application by Davidson with the Environmental Physics Group of the

Naval Postgraduate School, Monterey, California (1978). Additionally their research has provided a moist forced-entrainment model for mixed layer depth changes in the atmosphere that appears to have excellent possibilities for application to future fog prediction capability (Davidson, 1980).

More accurate understanding of subtle changes in the microphysics of the oceanic layer such as in the temperature structure function parameter, C_T^2, and the humidity structure function parameter, C_q^2, may only enhance the accuracy of open-ocean fog forecasting.

In the long term, successful objective forecast models will be integrated with the microphysics of the atmosphere as data stations and recording accuracy allow. In turn, this product will be blended with climatology, enhanced by the model output statistics approach as computer capability is increased, to present a consistent, accurate, easily-transmitted prediction product.

Of immediate impact is the fact that in the region of Ocean Weather Station Papa for the summer period, there now appears to be an accurate method for a single station to forecast fog formation and dissipation periods. All four of the open-ocean indices are within the measurement capability of any U.S. Naval Vessel. When recorded and plotted daily and when combined with a shore-based synoptic report and satellite links, they together will allow any single unit or task group

to predict with some confidence one of the most dangerous atmospheric phenomena to any open-ocean operation, the long duration advection fog with restricted visibilities of less than one kilometer.

APPENDIX A

ABRIDGED VERSION OF INTERNATIONALLY USED PRESENT WEATHER AND VISIBILITY CODES (UNITED STATES DEPARTMENTS OF COMMERCE, DEFENSE, AND TRANSPORTATION, 1969)

Present Weather

Code Value	Definition
00-03	Characteristic change of the state of the sky (cloud) during the past hour.
04-09	Haze, dust, sand, or smoke.
10	Deep light fog.
11-12	Shallow heavy fog.
13-17	Lightening, thunder, or precipitation within sight, not reaching the ground.
18-19	Squall(s), funnel cloud(s) during the past hour.
20	Drizzle during the past hour.
21-23	Rain, snow or rain and snow during the past hour.
24	Freezing drizzle during the past hour.
25-27	Shower(s) during the preceding hour.
28	Fog during the past hour.
29	Thunderstorm during the past hour.

Present Weather

Code Value	Definition
30-39	Duststorm, sandstorm, drifting or blowing snow.
40	Fog at distance, but not at station during the past hour (visibility less than 1 km).
41-49	Deep heavy fog at the time of observation (visibility less than 1 km).
50-59	Drizzle, or drizzle and rain.
60-63	Slight to moderate rain.
64-65	Heavy rain.
66	Slight freezing rain.
67	Moderate or heavy freezing rain.
68	Slight rain or drizzle and snow.
69	Moderate or heavy rain or drizzle and snow.
70-79	Solid precipitation not in showers.
80-89	Showery precipitation or precipitation with current or recent thunderstorms.

	Visibility
90	Less than 50 m
91	50-199 m
92	200-499 m
93	500 m - 0.99 km
94	1 - 1.99 km
95	2 - 3.99 km
96	4 - 9.99 km
97	10 - 19.99 km
98	20 - 49.99 km
99	50 km or more

Ship Station VV

Code Figure	Plot
90	<50 yds
91	50 yds
92	200 yds
93	1/4 NM
94	1/2
95	1
96	2
97	5
98	10
99	25

APPENDIX B

DATA SOURCES

Time Period	Observation Site	Data Available	Sources
July/August 1973	Ocean Weather Station Papa	Surface Observations (microfilm/ computer-tape)*	NWSD Asheville, N.C. of (NCC)**
		RAOBS (microfilm)	NWSD Asheville, N.C. of (NCC)
		Sea Surface Temperature (microfilm/computer-tape)	NWSD Asheville, N.C. of (NCC)
		Satellite Coverage	Space Science and Engineering Center University of Wisconsin, Madison
July/August 1977	Ocean Weather Station Papa	Surface Observations (microfilm/ computer-tape)	NWSD Asheville, N.C. of (NCC)
		RAOBS (microfilm)	NWSD Asheville, N.C. of (NCC)
		Sea Surface Temperature (microfilm/computer-tape)	NWSD Asheville, N.C. of (NCC)
		Sea Surface Temperature	Oceanographic observations at Ocean Station P Institute of Ocean Sciences, Patricia Bay, B.C.
		Satellite Coverage	Space Science and Engineering Center University of Wisconsin, Madison

*Computer-tape - Common marine tape format deck 128

**National Climatological Center

APPENDIX C

EXAMPLE OF LEIPPER FOG FORECAST PARAMETERS AND INDICES

A Worksheet from the Naval Weather Service Facility, San Diego.

1) PARAMETERS

a) Base of inversion on 12GMT sounding (SAN) ____ FT

b) Highest air temperature above base of inversion (SAN) Ta= ____ C

c) Sea temp at 0800LST on preceding day (Scripps) Tw= ____ C

d) Dew point temp at 1630 LST on preceding day (NZY) TD_p1630= ____ C

e) Mixing ratio at 10,000' on the 12GMT SAN sounding MR= ____ g/kg

2) INDICES

		FAVORABLE	UNFAVORABLE
a)	Base of inversion= ____ FT	Below 1300'	Above 1300'
b)	Ta minus Tw = ____ C	Above 0 C	Below 0 C
c)	TD_p1630 minus Tw= ____ C	Above -5 C	Below -5
d)	MR at 10,000' = ____ g/kg	Less than 3.5 g/kg	More than 3.5 g/kg

NOTE: All must be favorable for forecast to become favorable to indicate fog formation.

3) Forecast and Verification

a) Forecast valid for period 1800-0600 LST following time of observation used in computations.

b) Verification (circle one)

Visibility	Above 2 miles		Below 2 miles	
Obstruction to vision	Fog	Ground Fog	Haze	None

COMPUTED BY: ____________

DATE: ____________________

APPENDIX D

OPEN OCEAN FOG FORECAST VARIABLES AND INDICES

Parameters

1. Inversion Height (mb) (00Z)
2. Wind Direction (°T) and Wind Speed (knots) (00Z, 12Z)
3. Sea Surface Temperature (°C) (00Z, 12Z)
4. Dew Point Temperature (°C) (00Z, 12Z)
5. Maximum Temperature (air) above the Inversion (°C) (00Z)

Indices

	Favorable	Unfavorable
1. Inversion Height (00Z)	Below 1000'	Above 1000'
2. Temperature Index- Maximum temperature above inversion (00Z) minus sea surface temperature at (00Z) the preceding day.	Values greater than 0°C	Values less than 0°C
3. Moisture Index - Dew point (00Z) minus the sea surface temperature at 00Z the preceding day.	Values greater than -0.5°C	Values less than -0.5°C
4. Advection Index - Wind direction (°T) and Speed (knots)	Winds greater than or equal to 3, less than or equal to 15;120-290°T	Winds greater than 15 knots 291-119°T

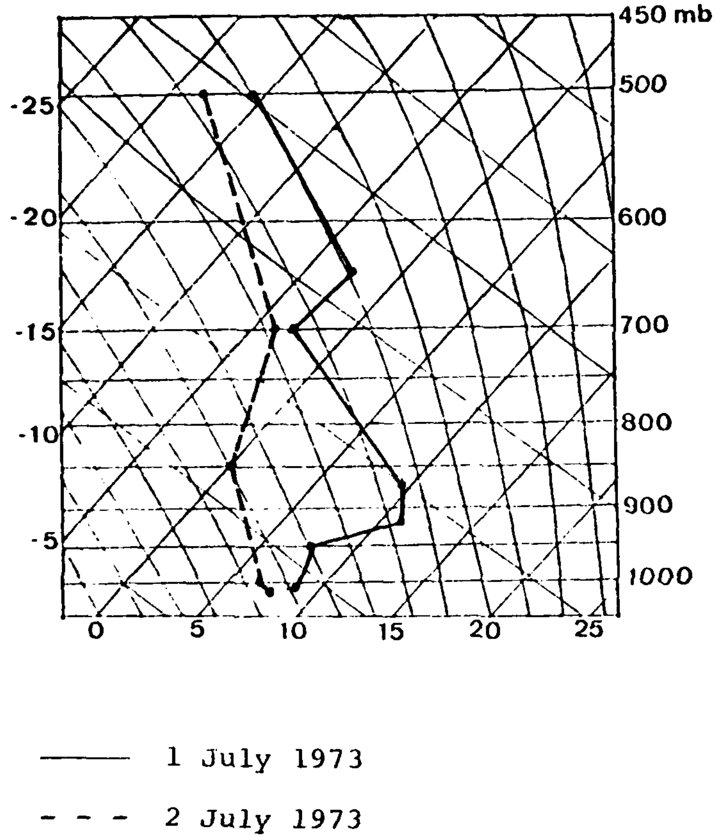
Note: 1. All must be favorable to forecast fog at the recording station.

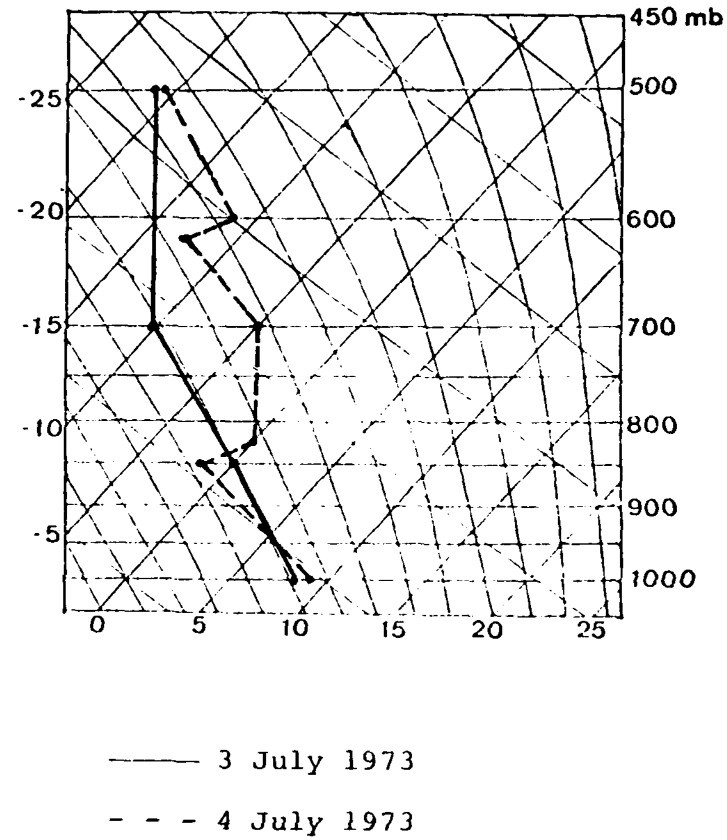
2. Forecast is valid for 24 hours (1400 local of the recording day through 1400 local of the following day).

APPENDIX E

DAILY RAOB PLOTS

(DOD)
USAF SKEW T, log p DIAGRAM
(SELECT PORTION)





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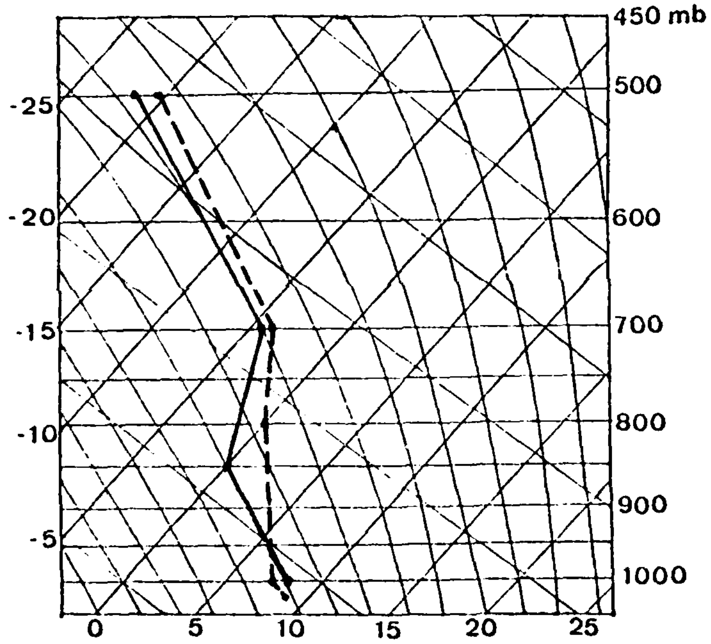

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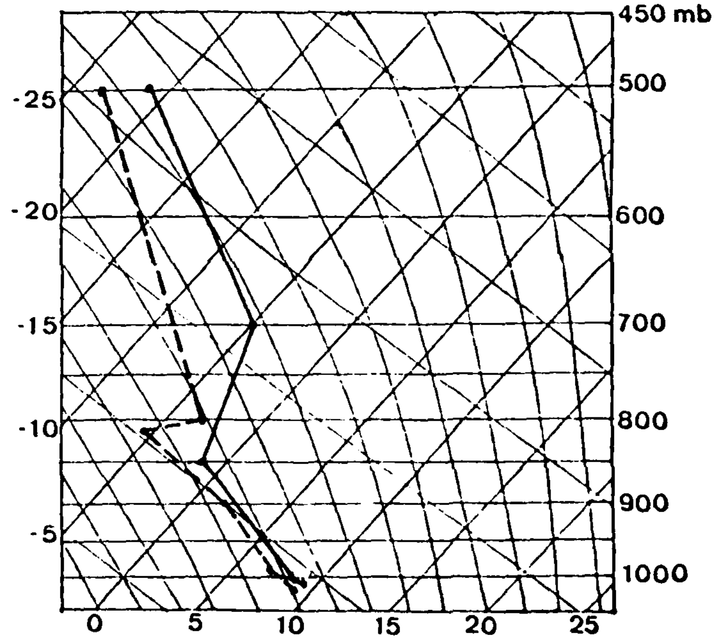

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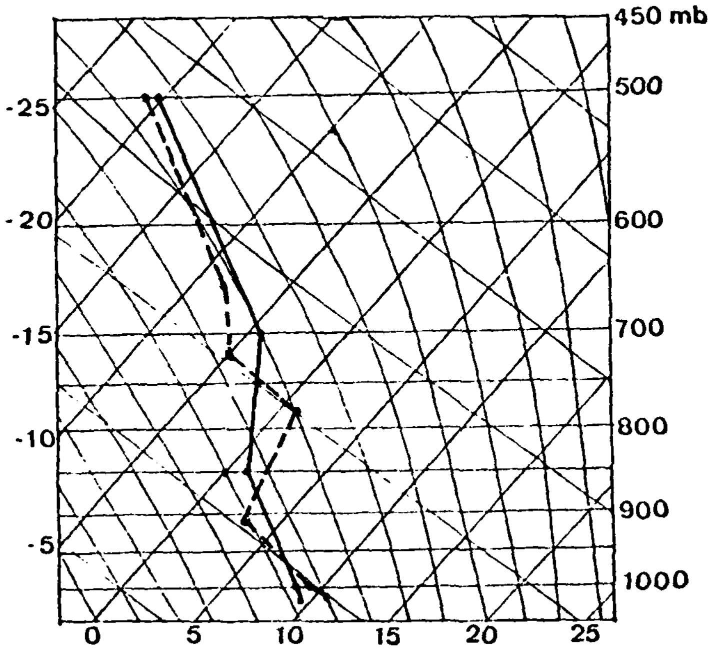
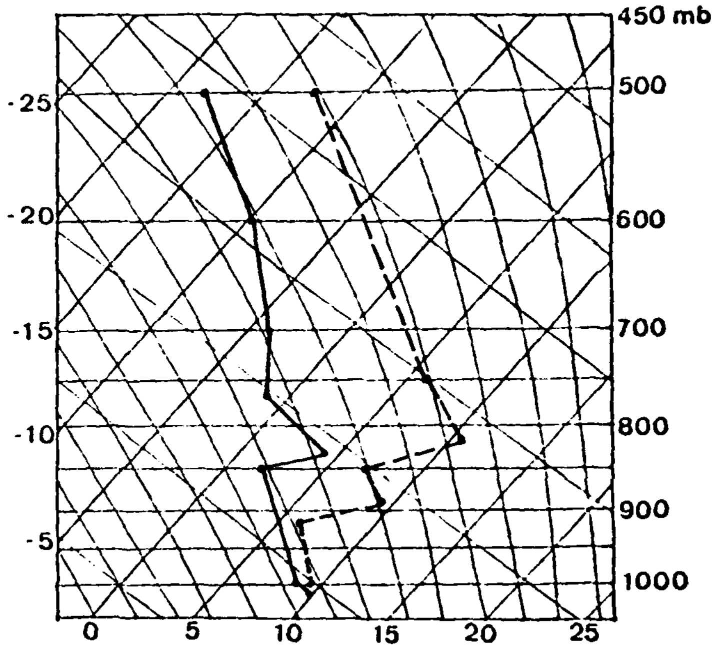


—— 9 July 1973

- - - 10 July 1973



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- - - 12 July 1973

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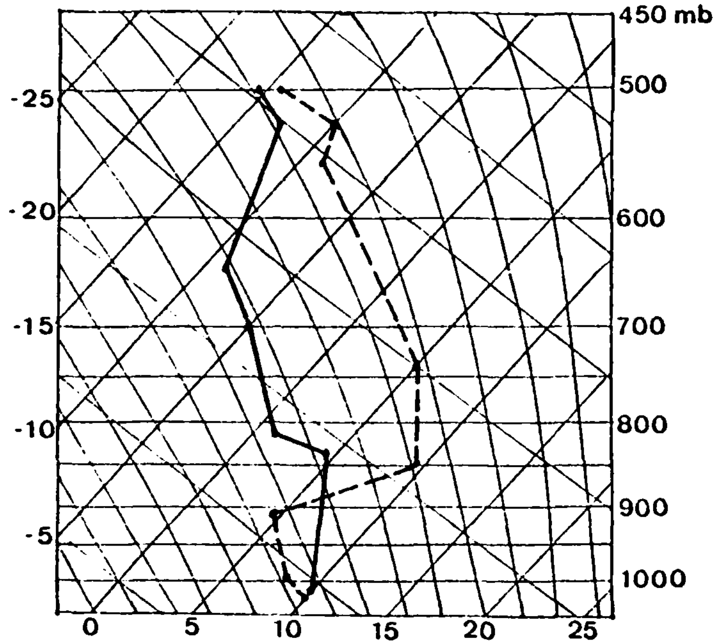

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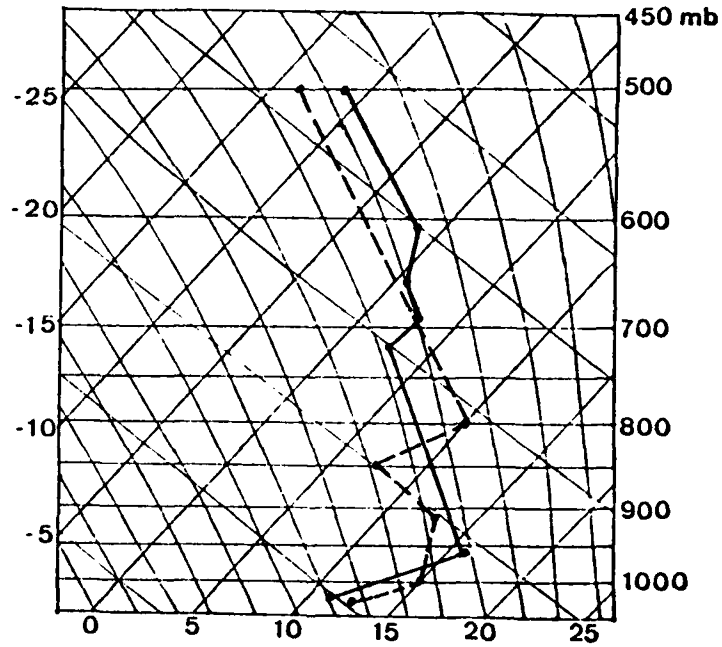

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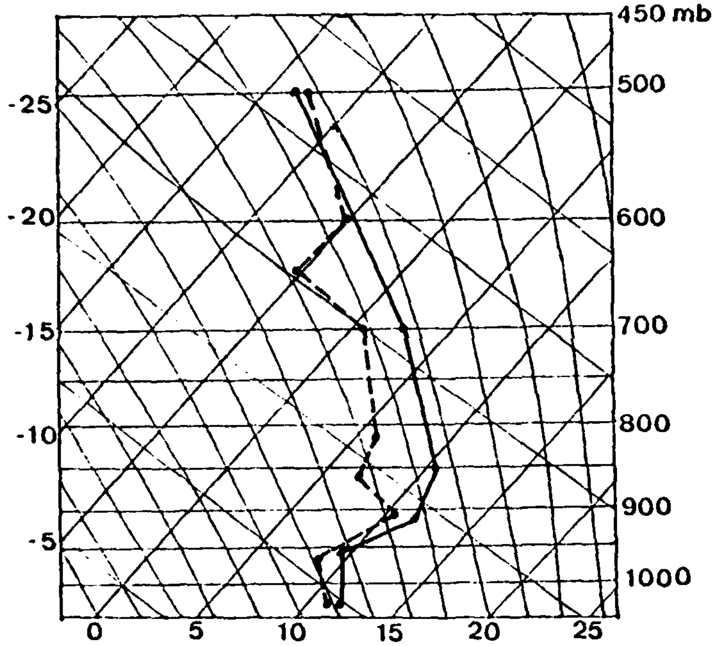

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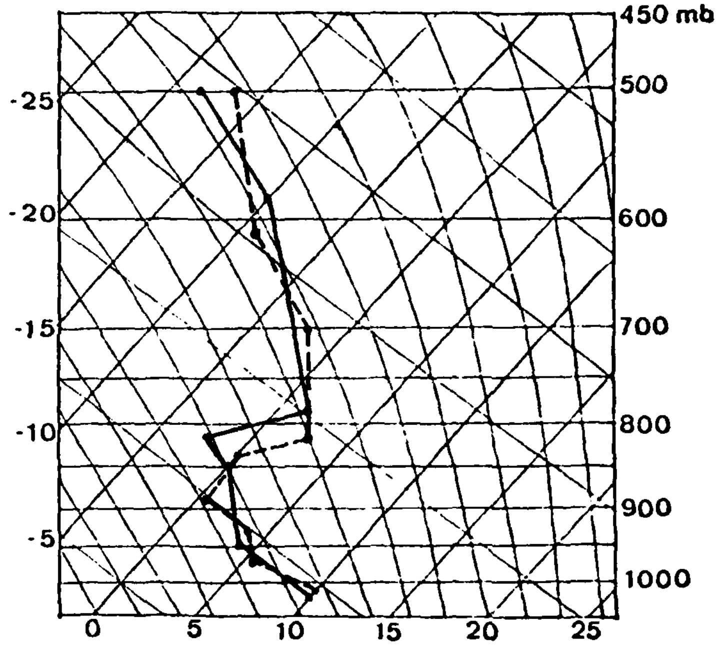

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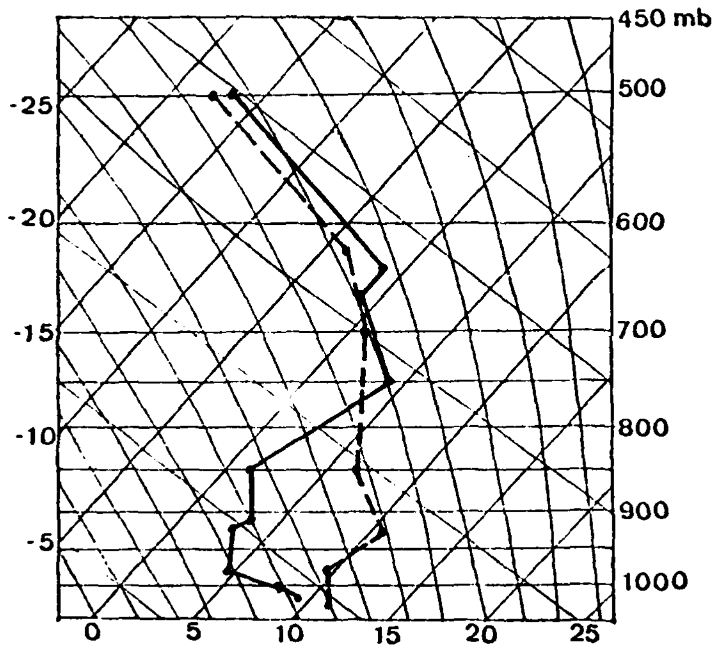

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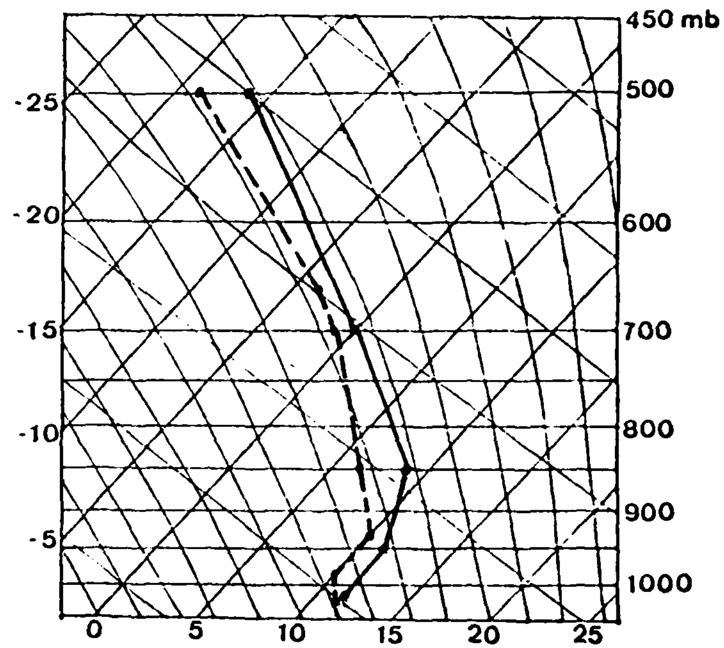

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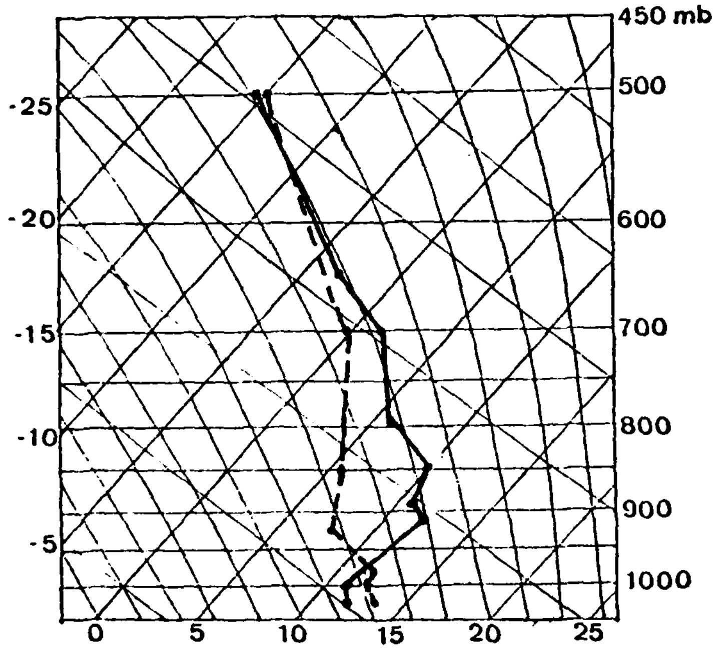

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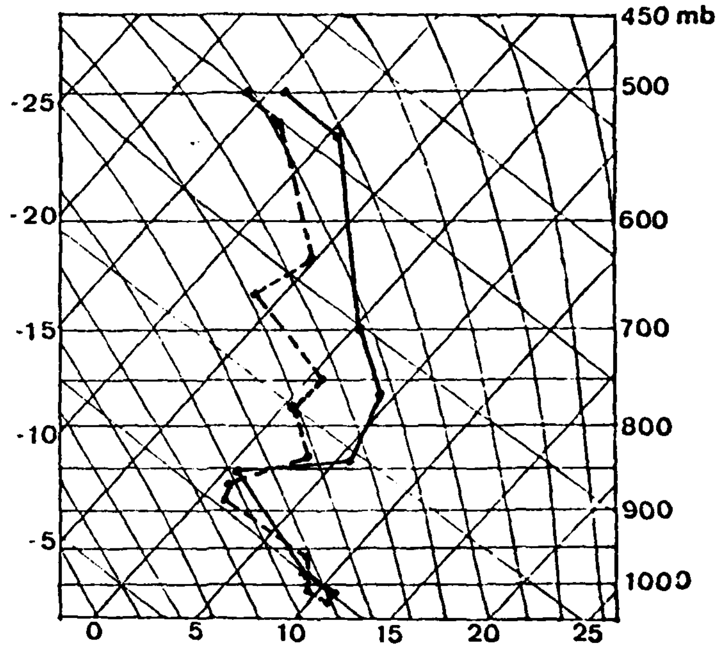

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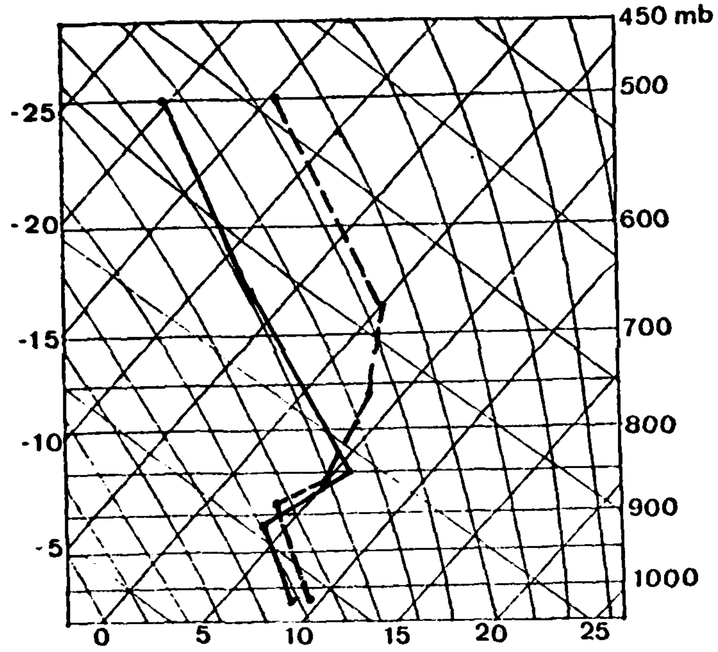
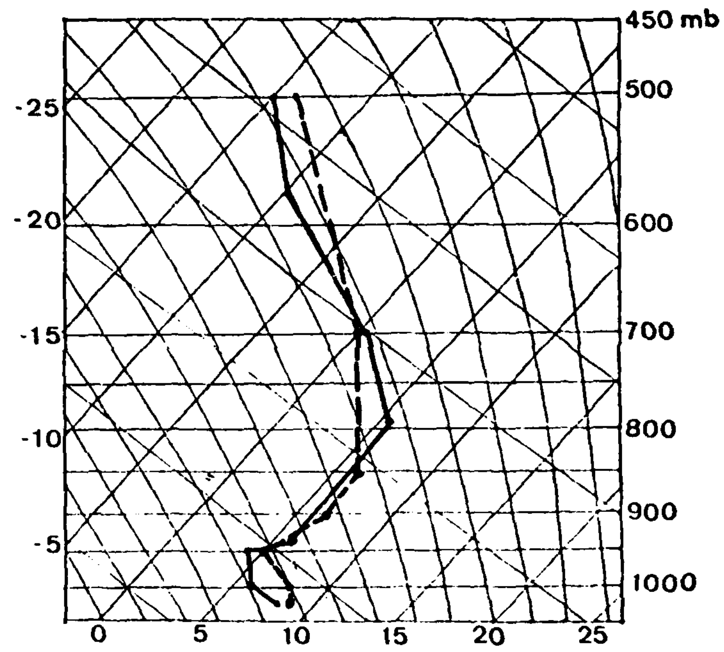


—— 1 July 1977

- - - 7 July 1977



—— 8 July 1977

- - - 9 July 1977

(DOD)

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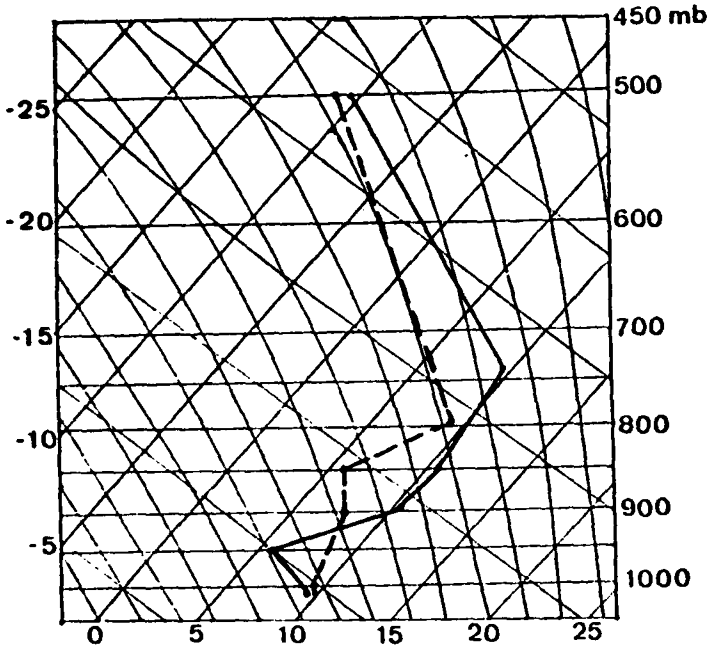
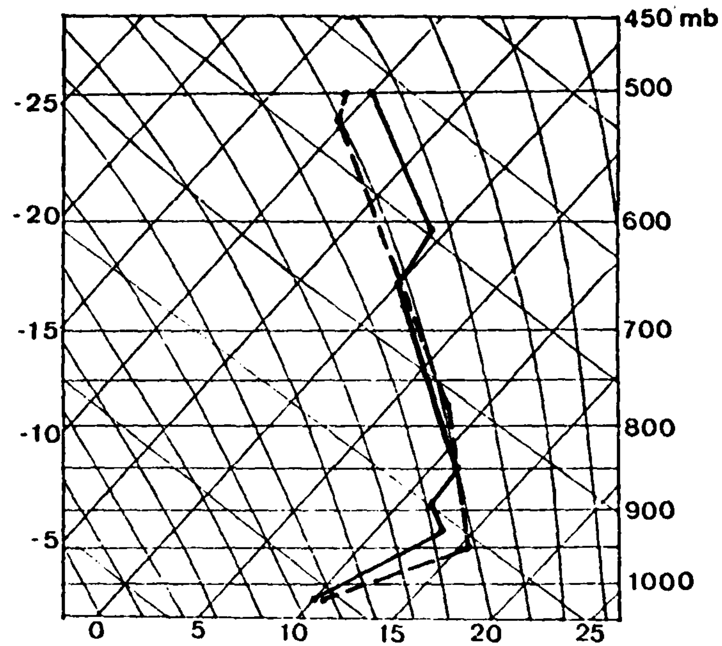


——— 10 July 1977

- - - 11 July 1977



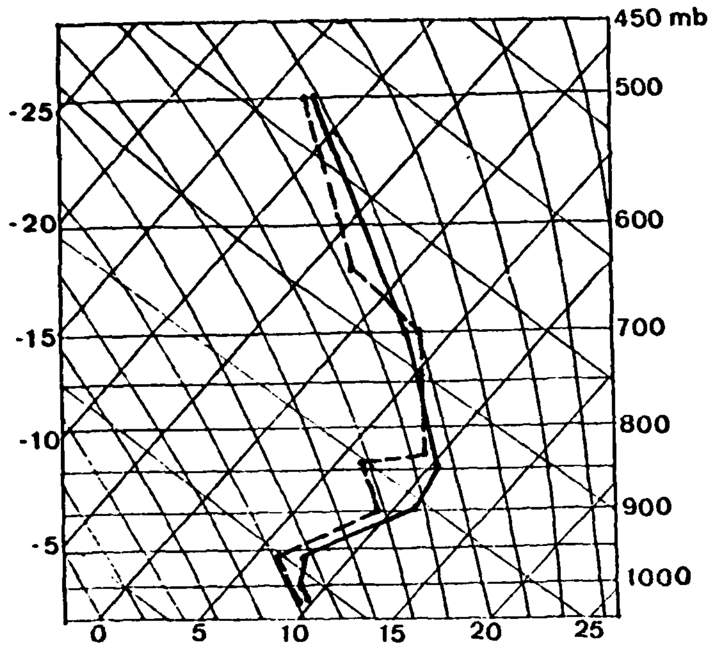
——— 12 July 1977

- - - 13 July 1977

(DOD)

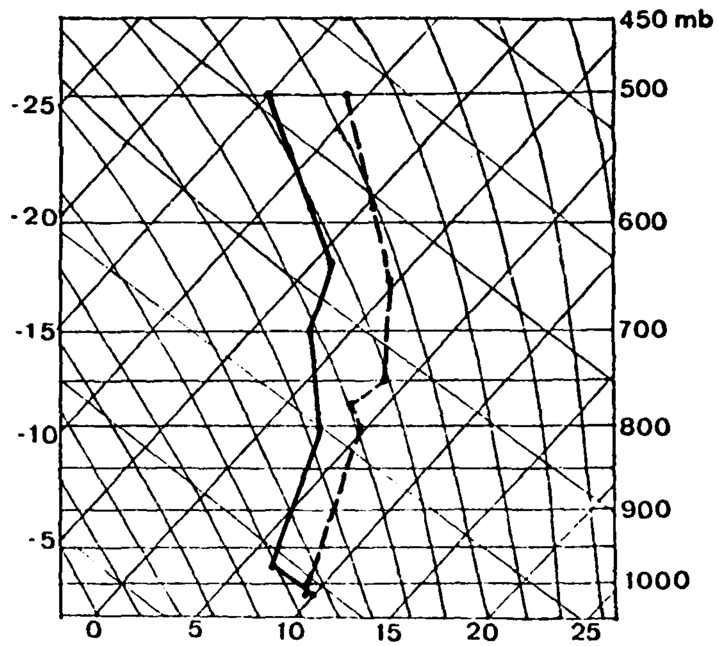
USAF SKEW T, log p DIAGRAM

(SELECT PORTION)



—— 14 July 1977

- - - 15 July 1977



—— 16 July 1977

- - - 17 July 1977

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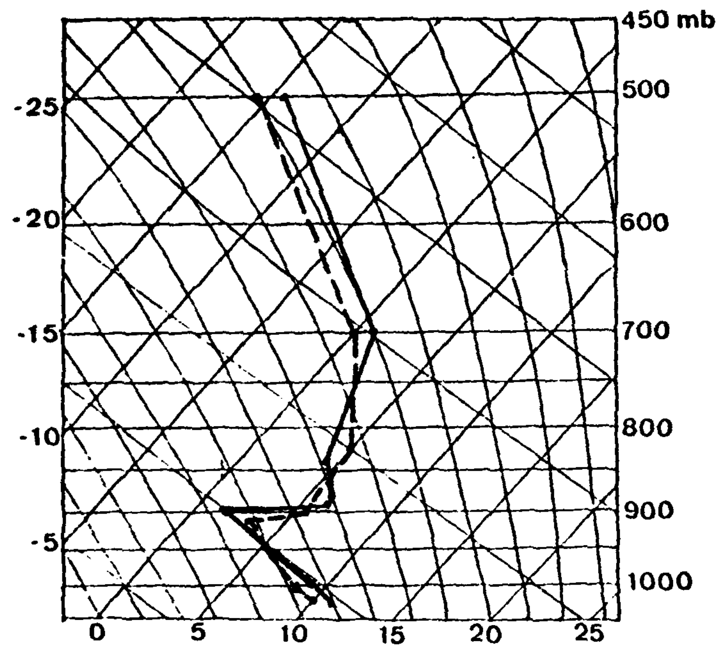
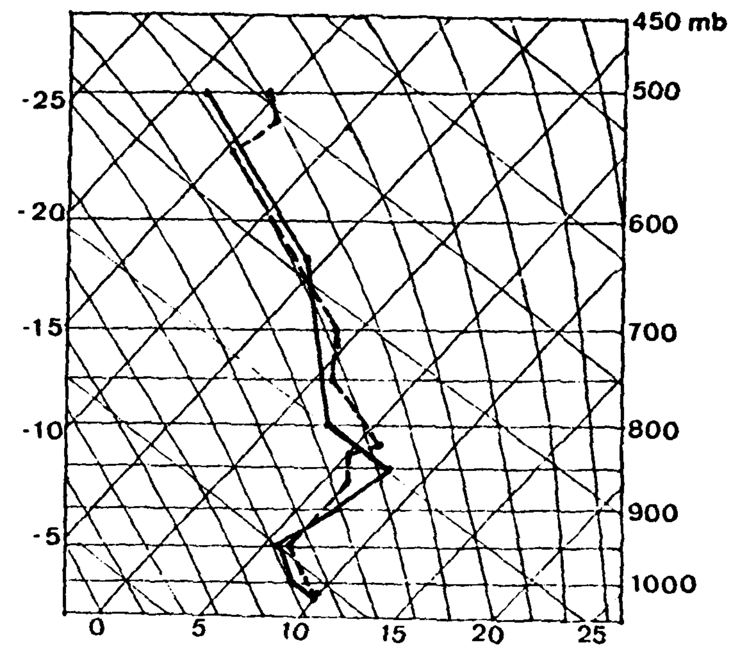


—— 18 July 1977

- - - 19 July 1977



—— 20 July 1977

- - - 21 July 1977

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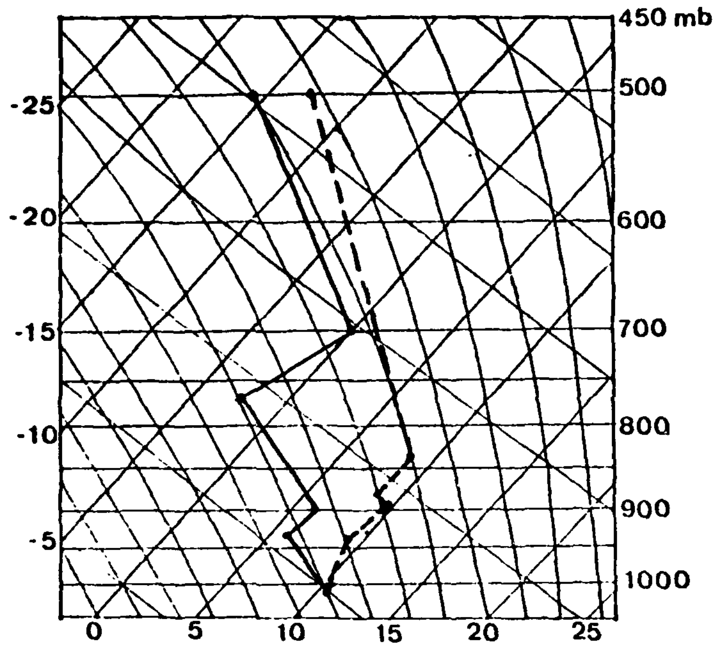
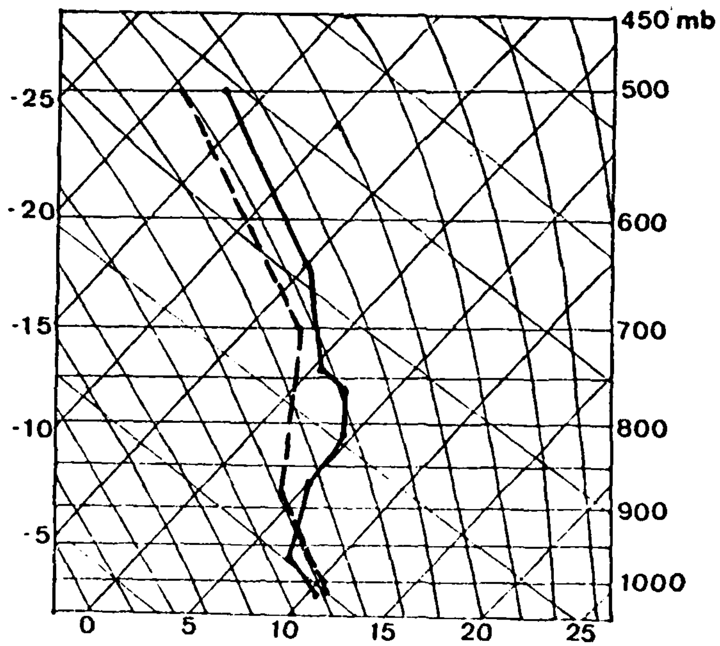


—— 22 July 1977

- - - 23 July 1977



—— 24 July 1977

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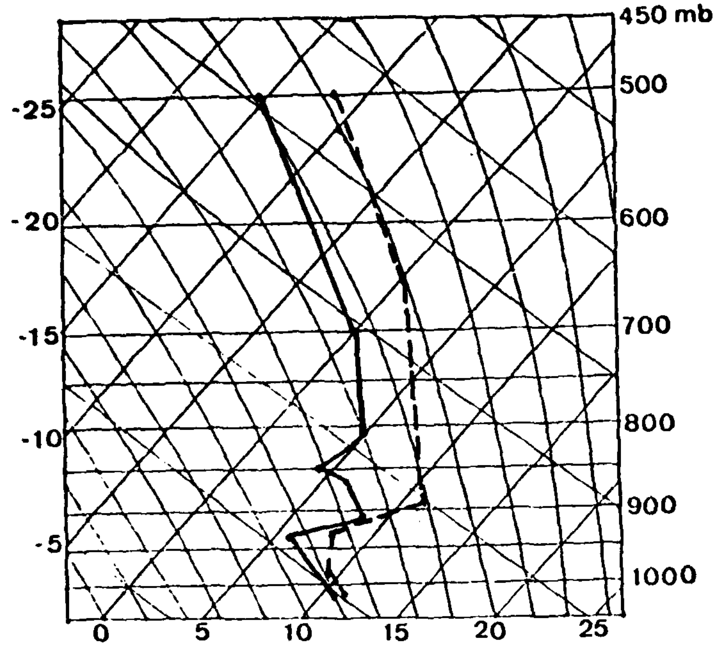
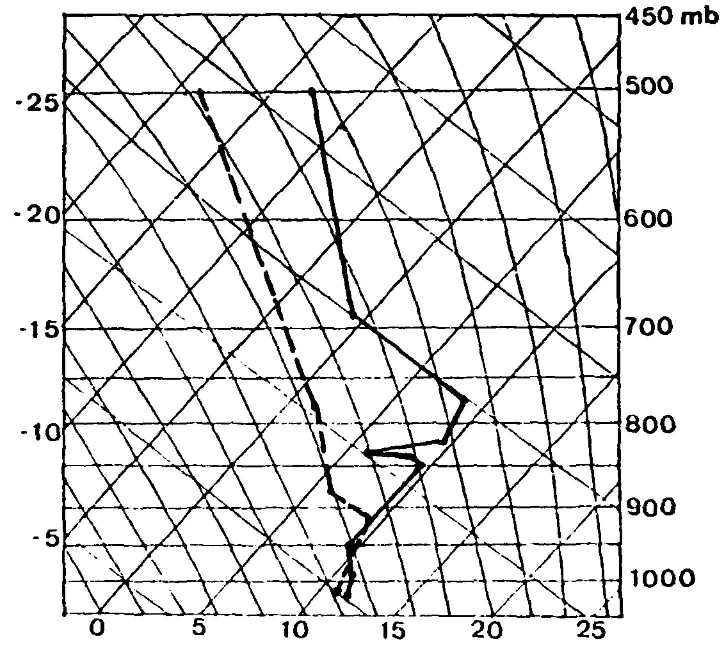


—— 26 July 1977

- - - 27 July 1977



—— 28 July 1977

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(DOD)

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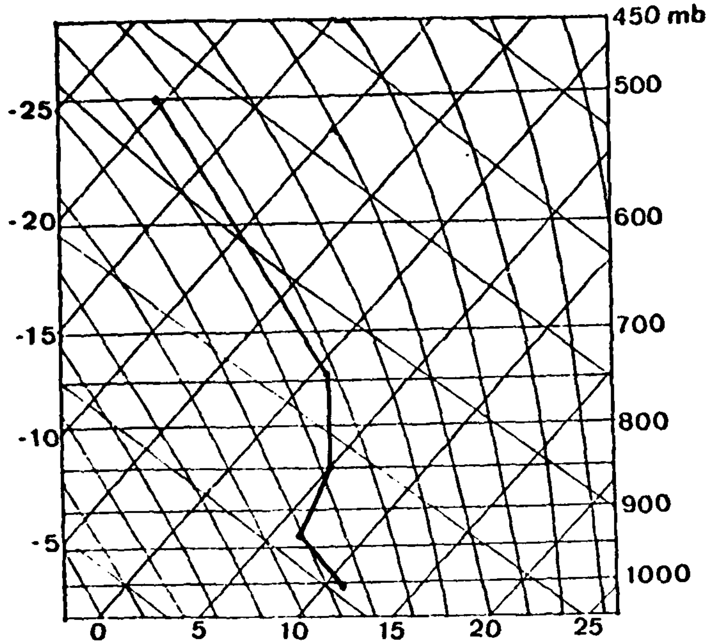
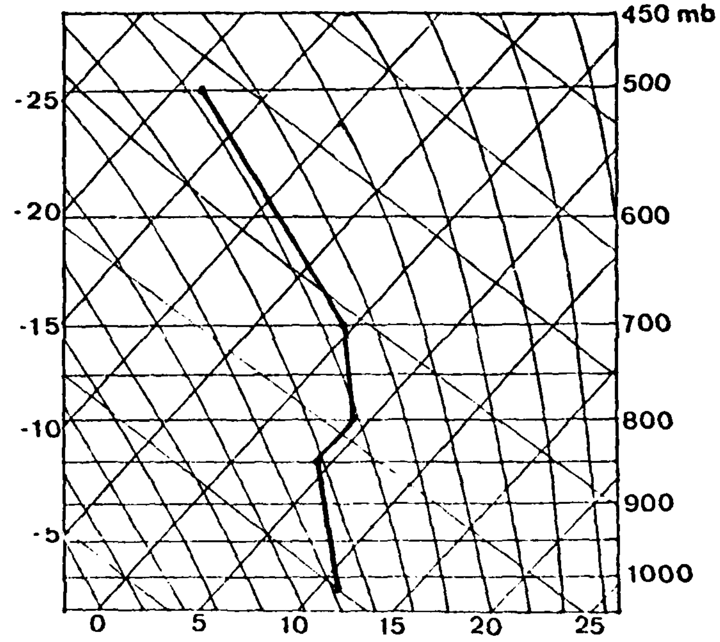


——— 30 July 1977



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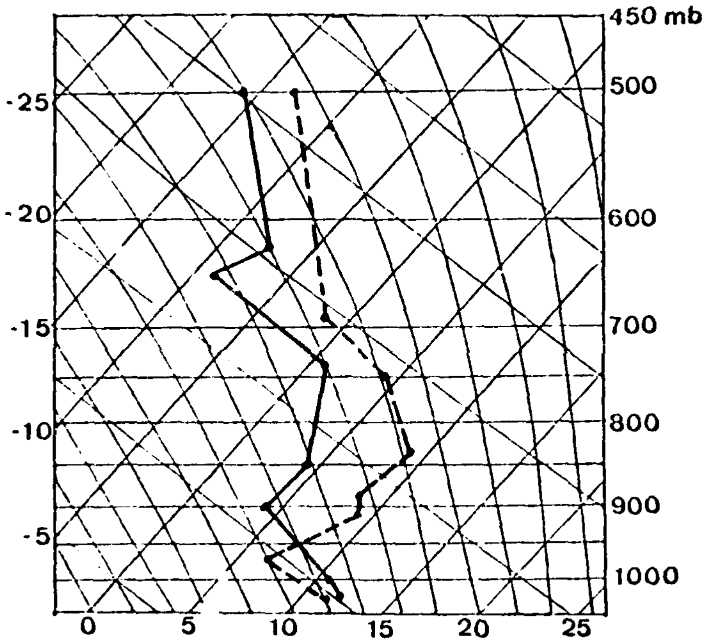
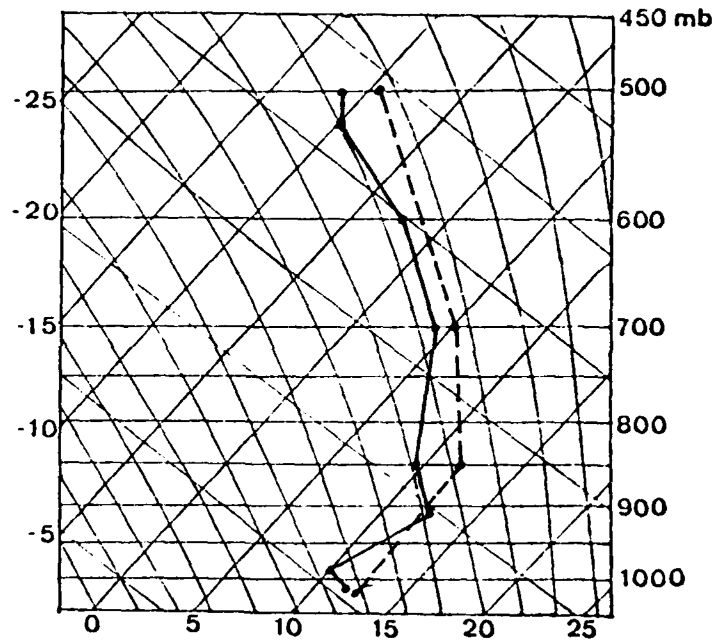


——— 1 August 1973

- - - 2 August 1973



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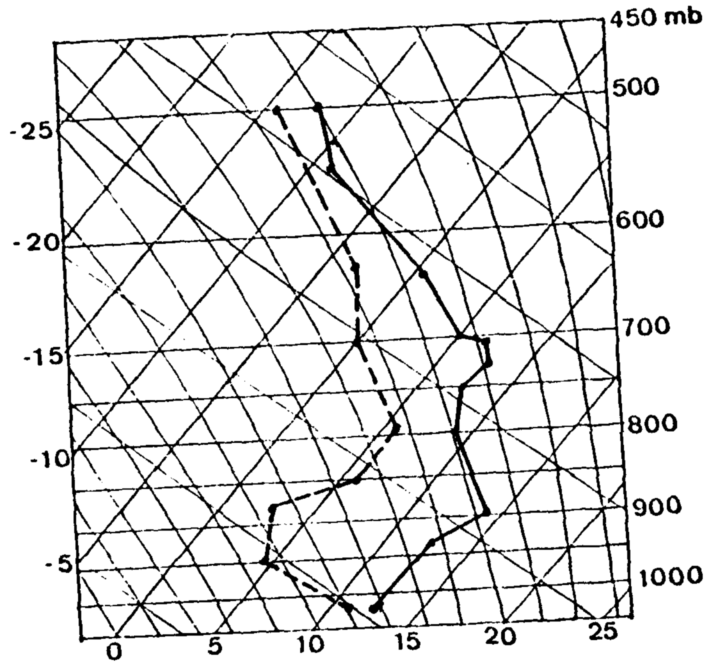
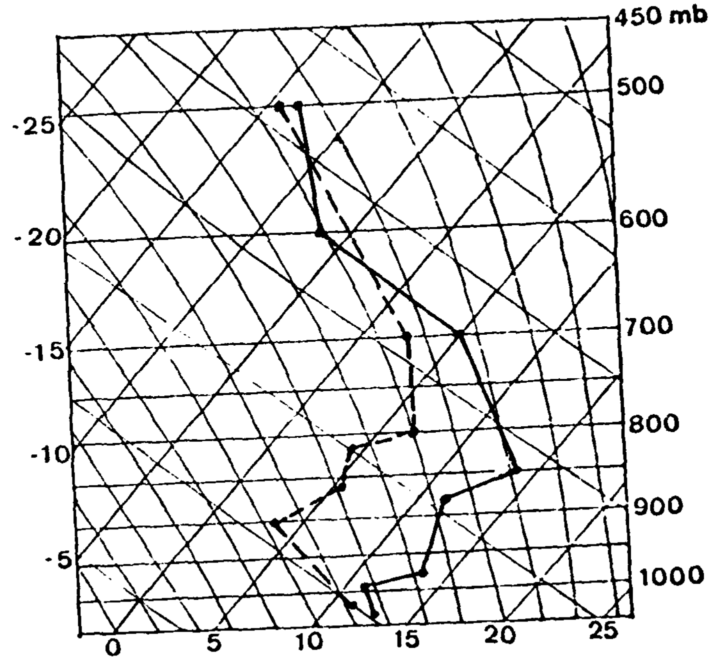


——— 7 August 1973

- - - 9 August 1973



——— 11 August 1973

- - - 13 August 1973

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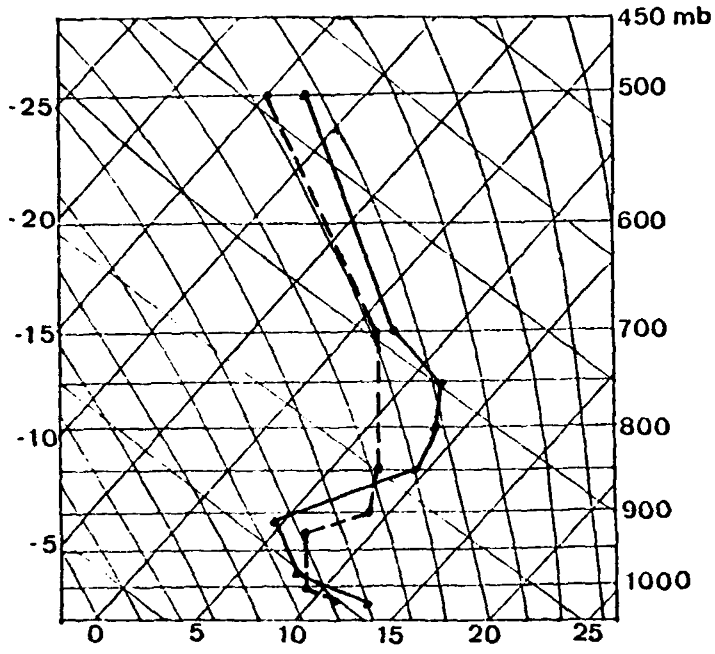

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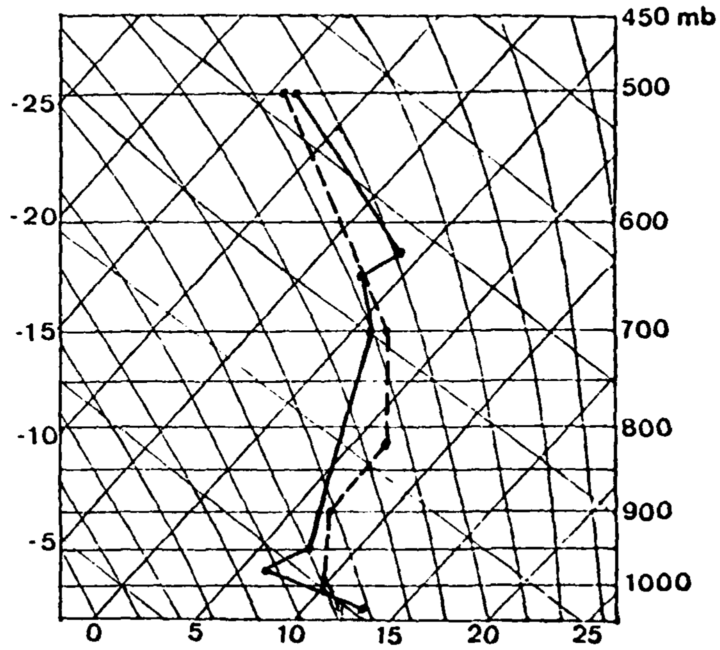
- - - 15 August 1973



—— 16 August 1973

- - - 17 August 1973

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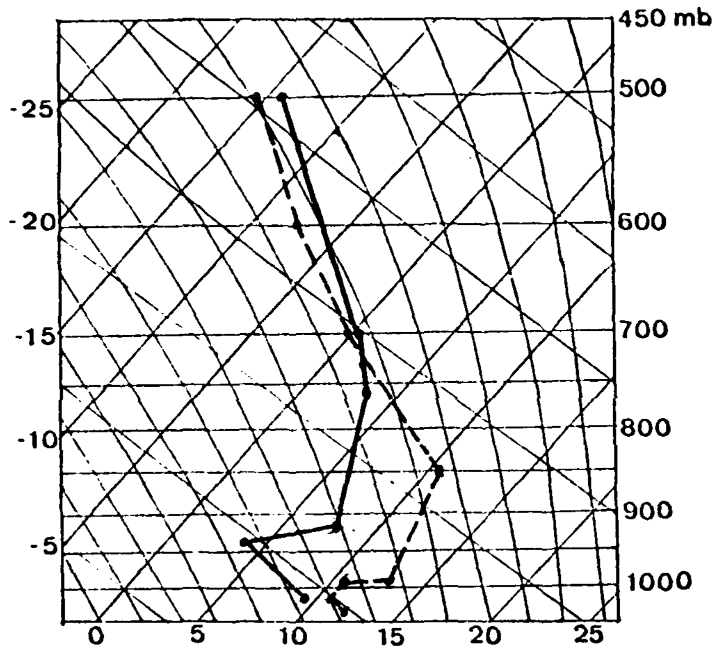

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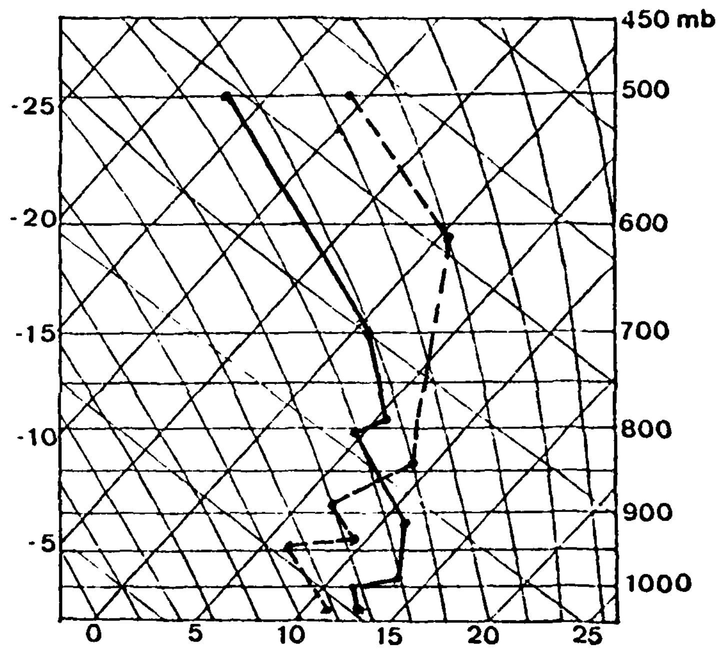
- - - 20 August 1973



—— 21 August 1973

- - - 22 August 1973

(DOD)

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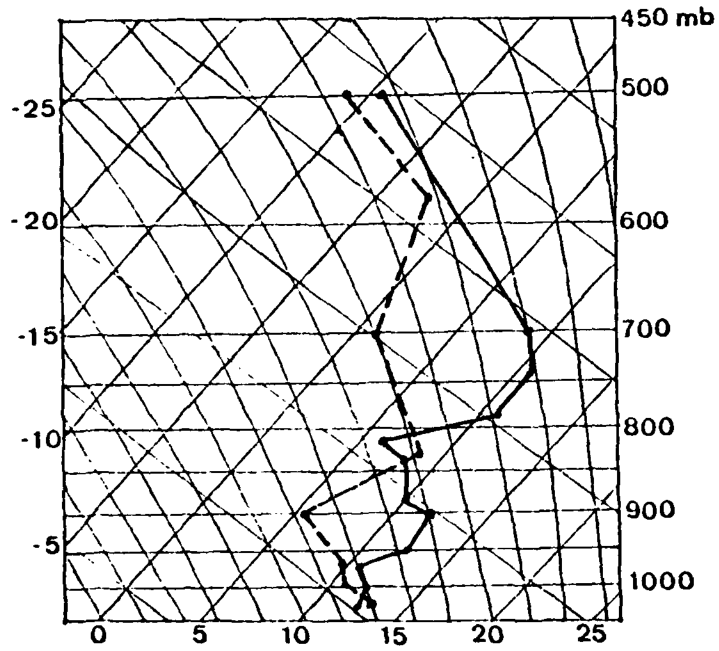
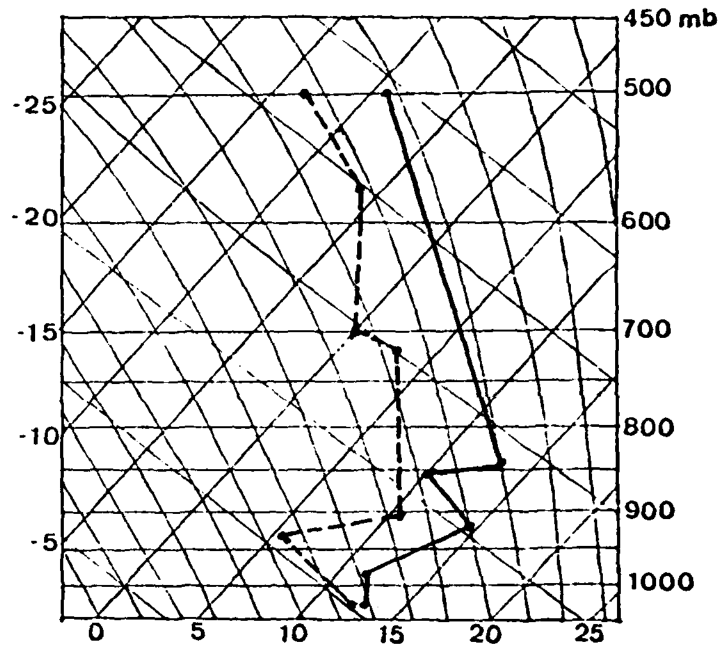
(SELECT PORTION)



—— 23 August 1973

- - - 24 August 1973



—— 25 August 1973

- - - 26 August 1973

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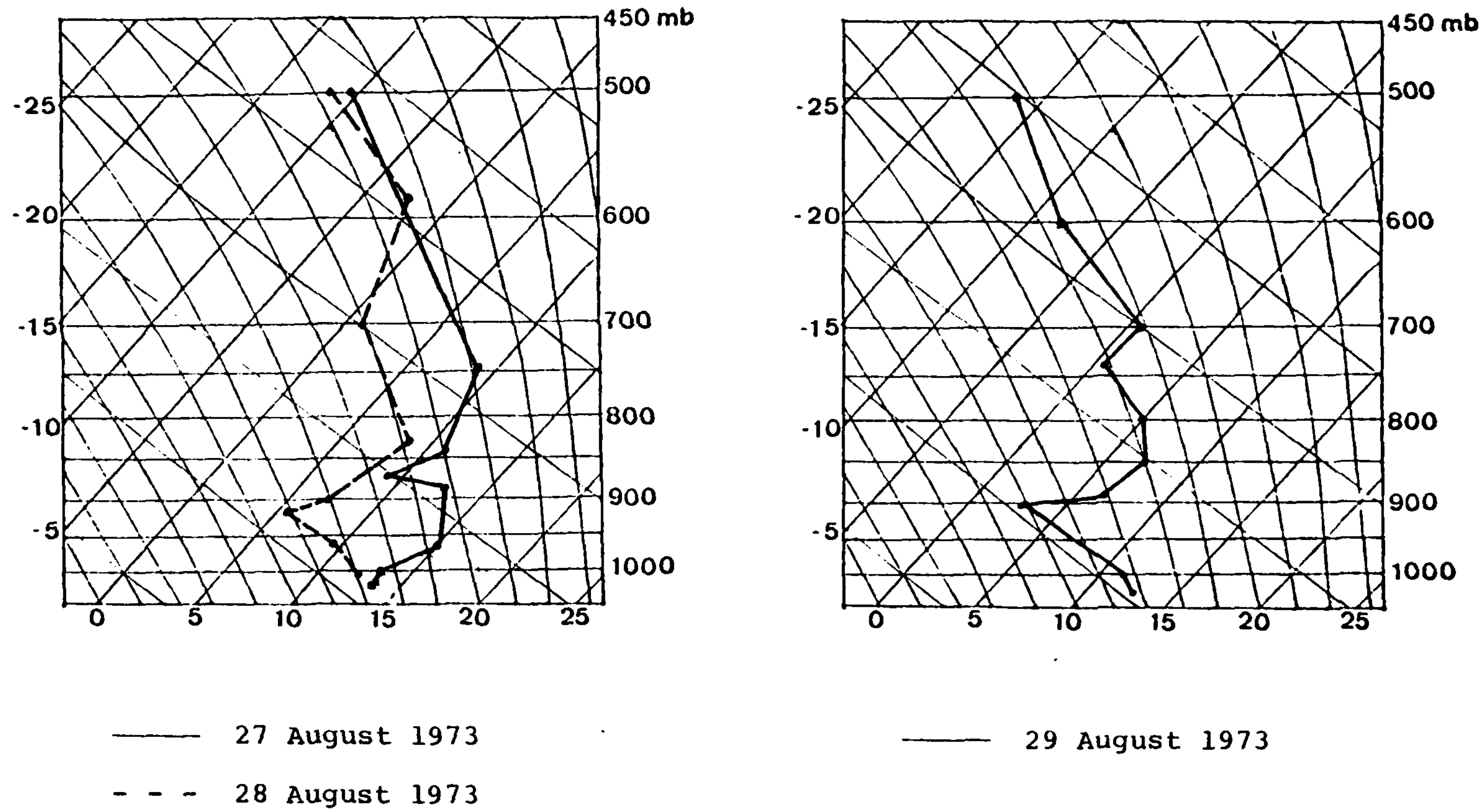

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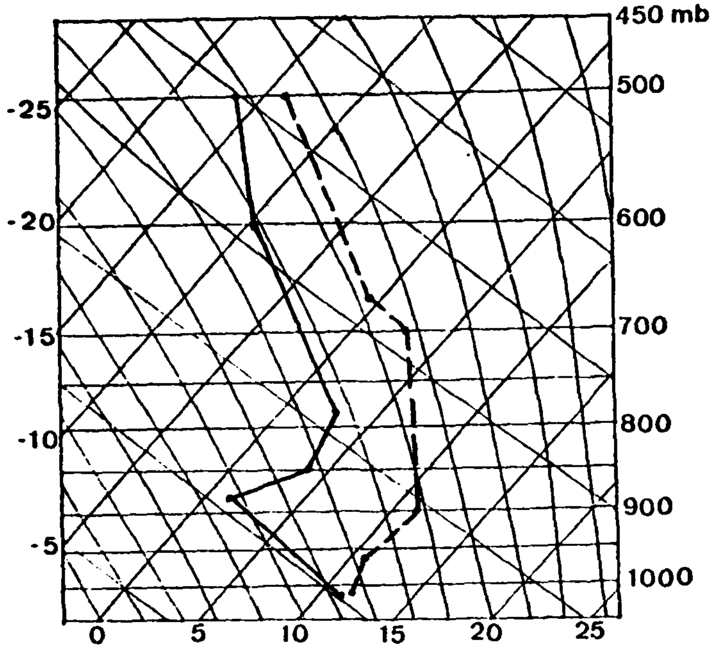
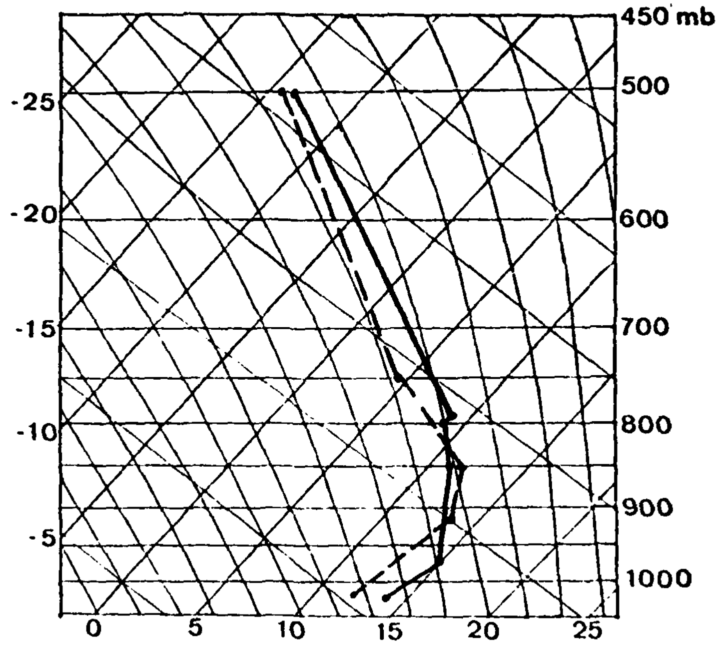
(SELECT PORTION)



——— 1 August 1977

- - - 2 August 1977



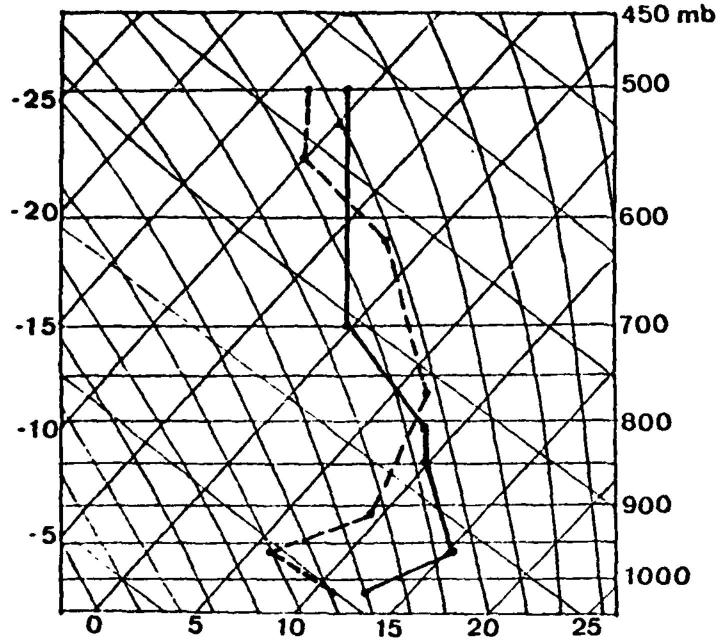
——— 3 August 1977

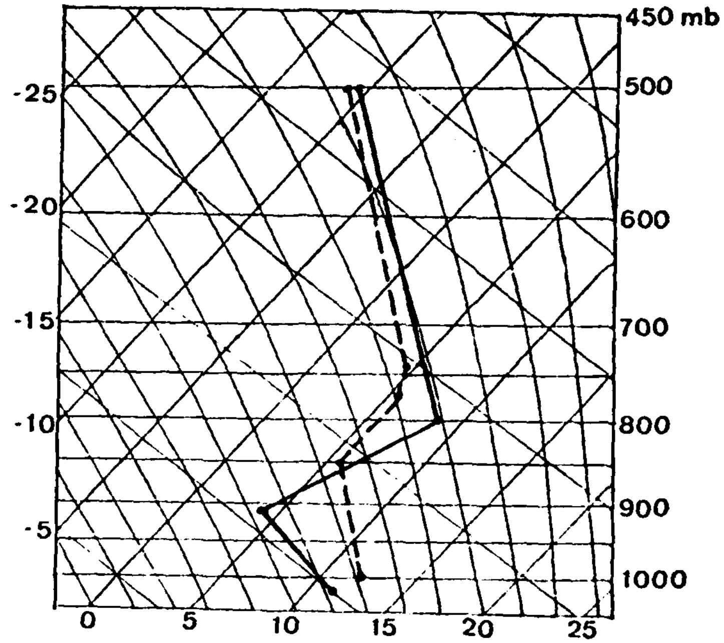
- - - 4 August 1977

(DOD)

USAF SKEW T, log p DIAGRAM

(SELECT PORTION)





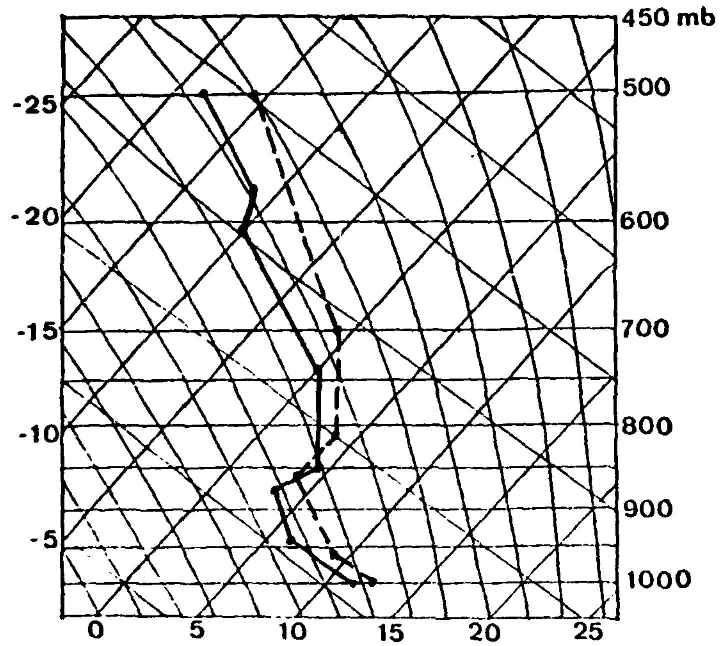
——— 5 August 1977

- - - 6 August 1977

——— 7 August 1977

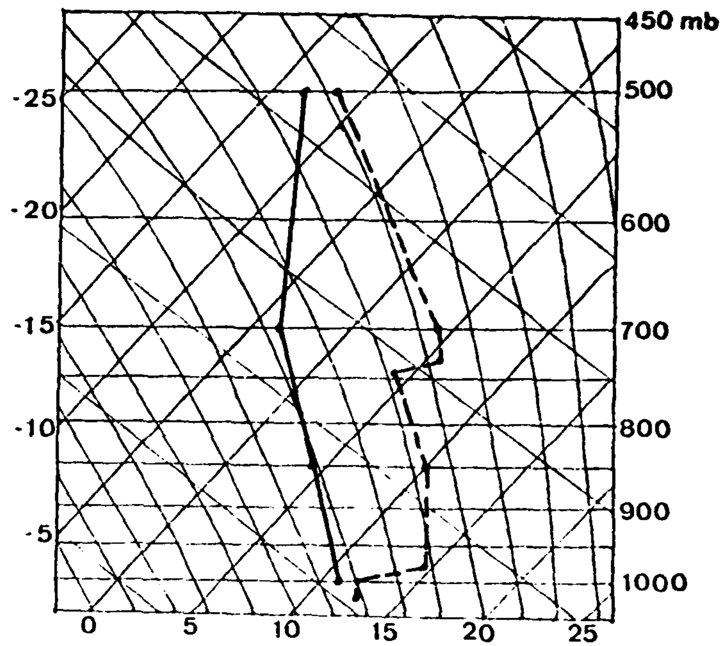
- - - 8 August 1977

(DOD)
USAF SKEW T, log p DIAGRAM
(SELECT PORTION)



——— 9 August 1977

- - - 10 August 1977



——— 11 August 1977

- - - 12 August 1977

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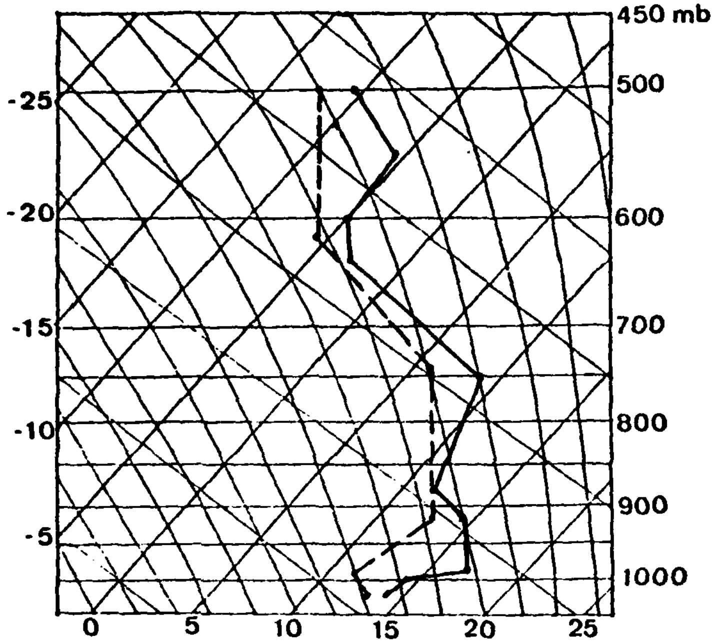
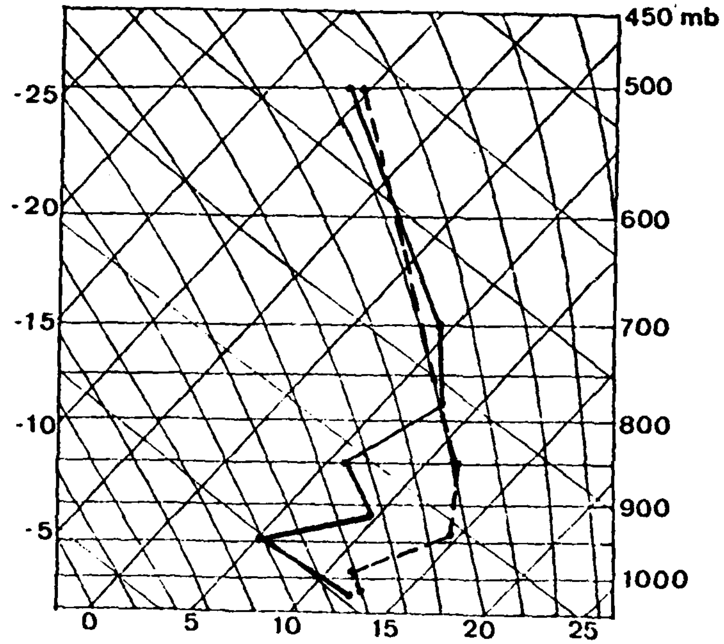


—— 13 August 1977

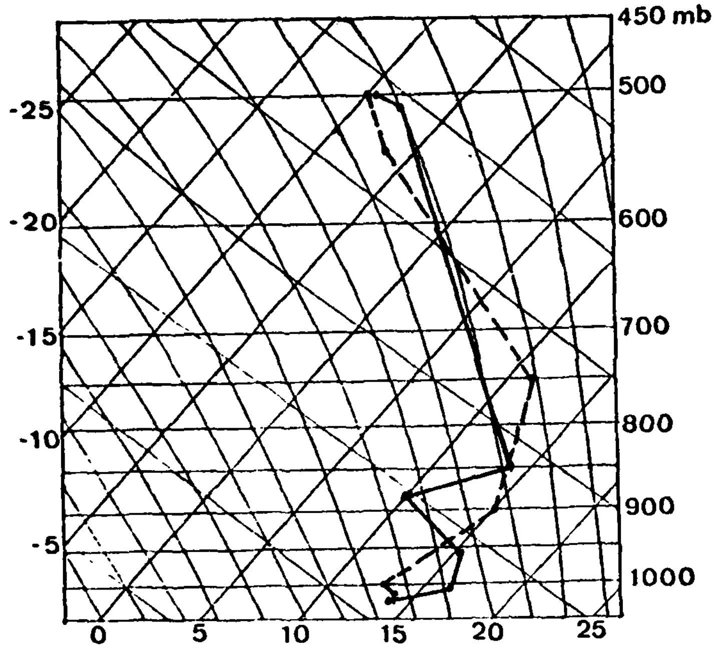
- - - 14 August 1977



—— 15 August 1977

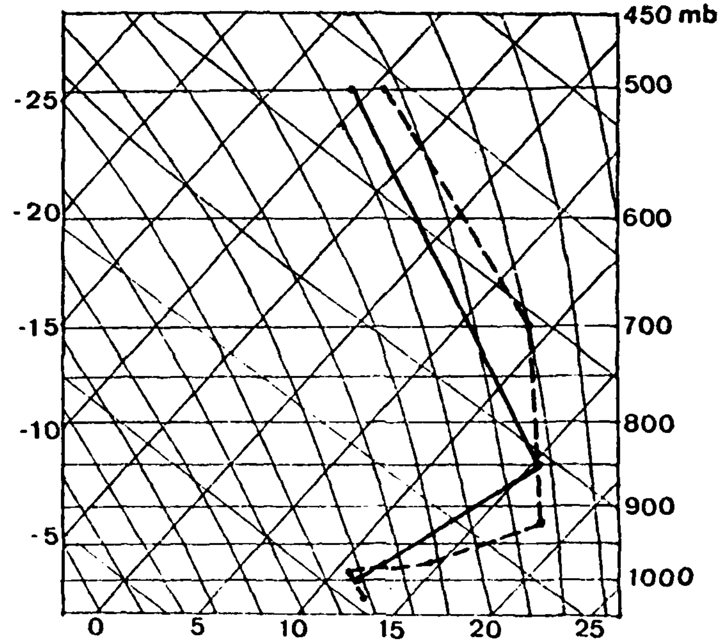
- - - 16 August 1977

(DOD)
USAF SKEW T, log p DIAGRAM
(SELECT PORTION)



——— 17 August 1977

- - - 18 August 1977



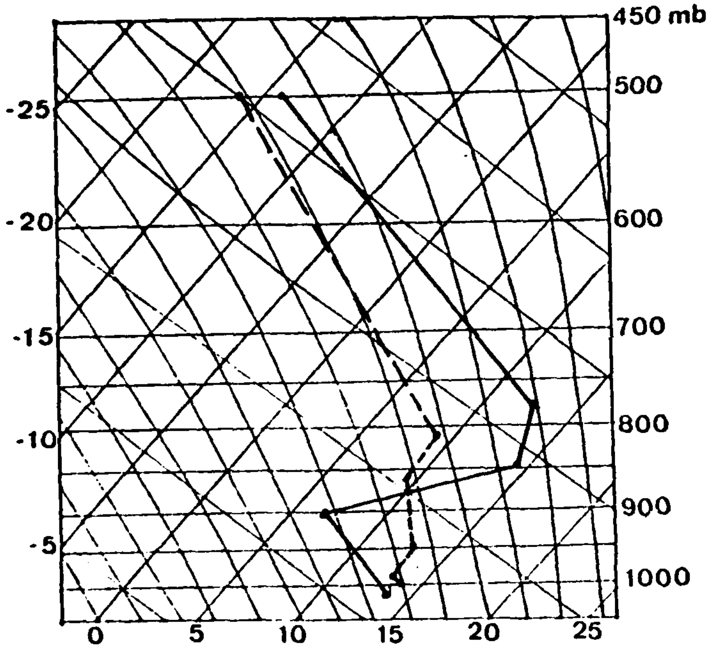
——— 19 August 1977

- - - 20 August 1977

(DOD)

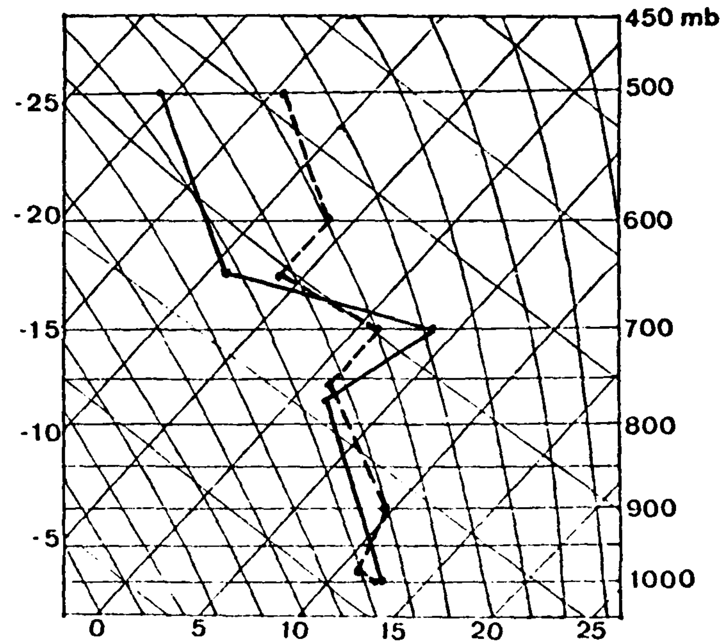
USAF SKEW T, log p DIAGRAM

(SELECT PORTION)



—— 21 August 1977

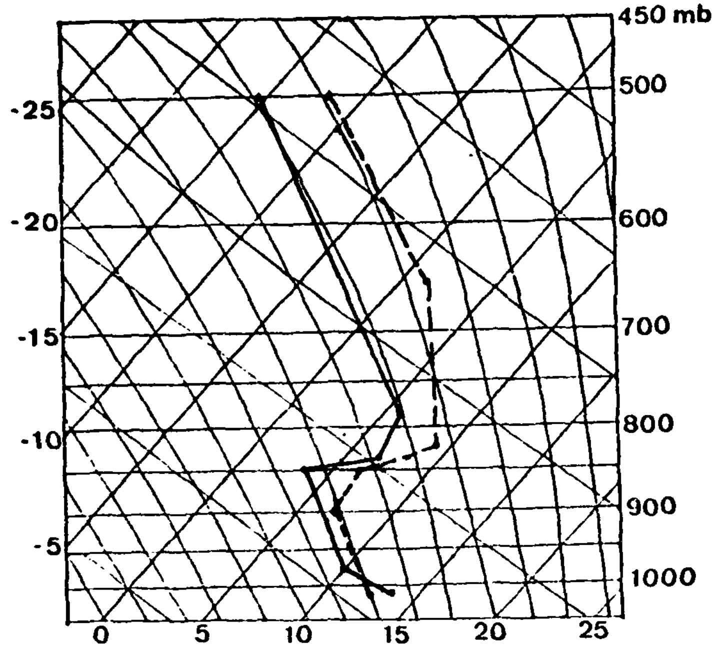
- - - 22 August 1977



—— 23 August 1977

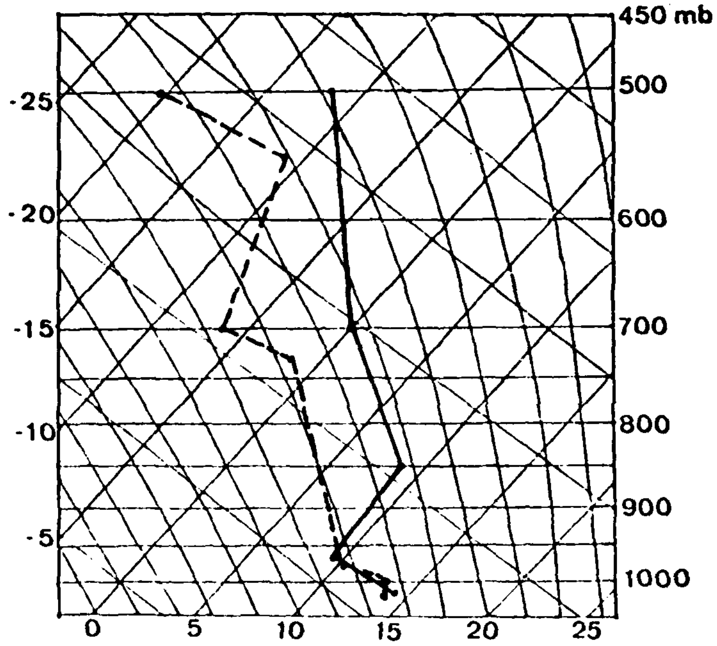
- - - 24 August 1977

(DOD)
USAF SKEW T, log p DIAGRAM
(SELECT PORTION)



—— 25 August 1977

- - - 26 August 1977



—— 27 August 1977

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(DOD)

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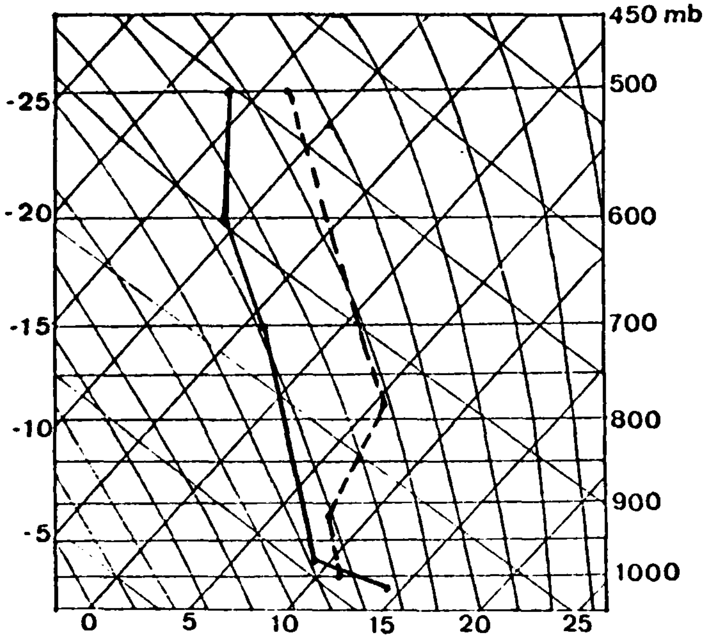
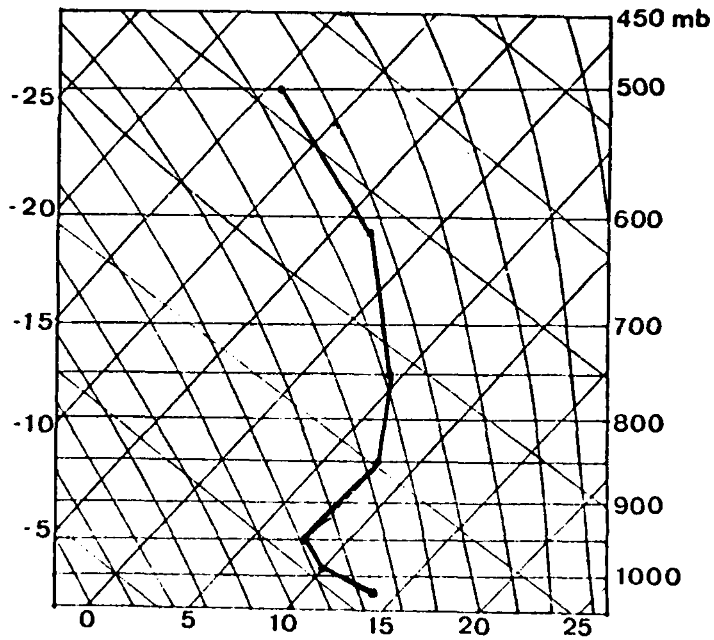


—— 29 August 1977

- - - 30 August 1977



—— 31 August 1977

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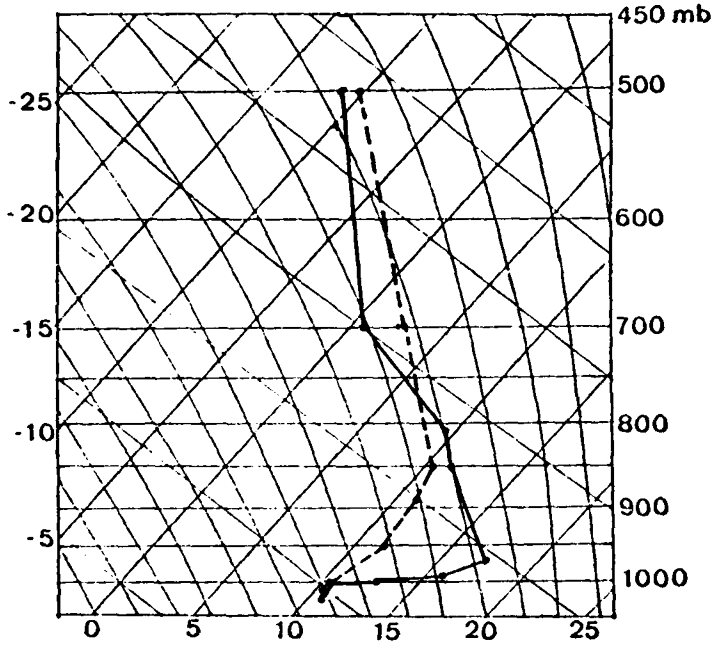
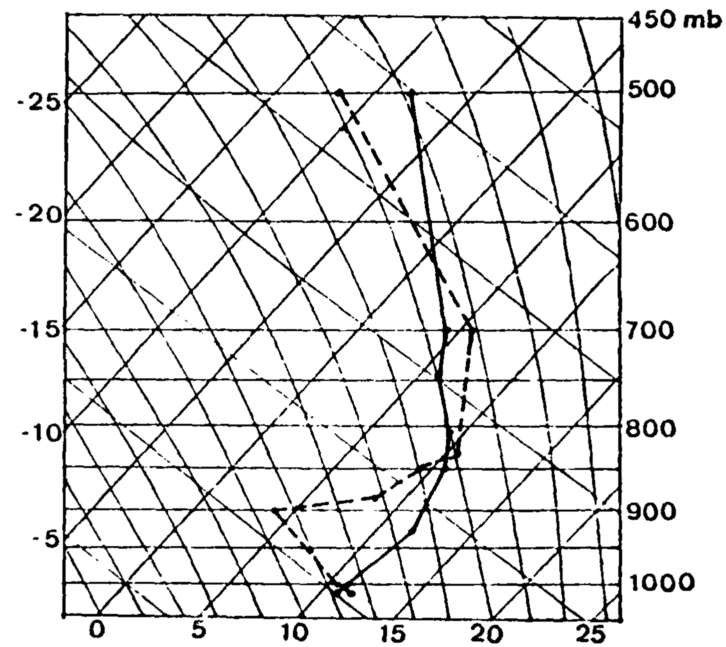


—— 1 July 1975

- - - 2 July 1975



—— 3 July 1975

- - - 4 July 1975

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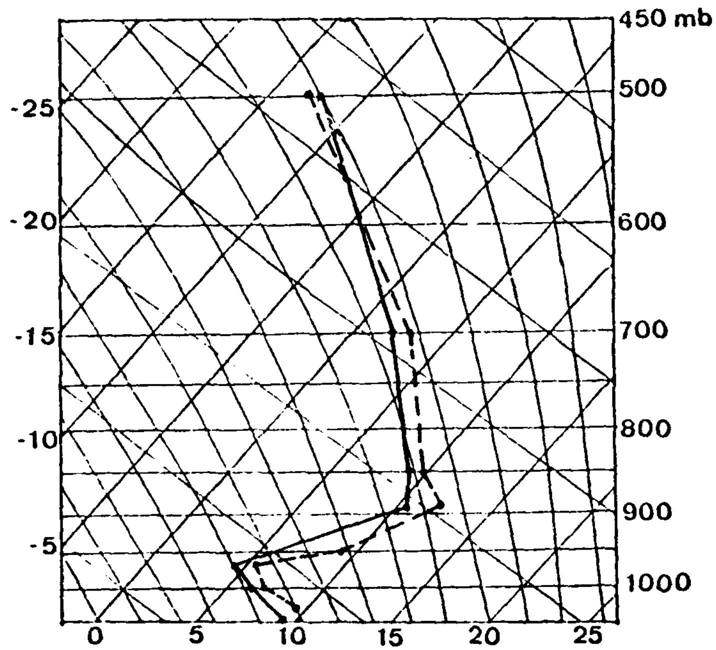

——— 5 July 1975

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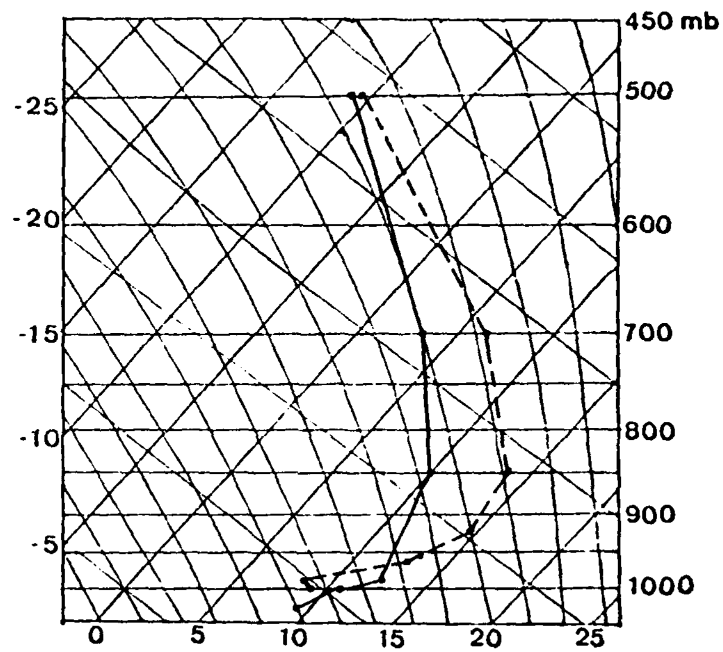

——— 7 July 1975

- - - 8 July 1975

(DOD)

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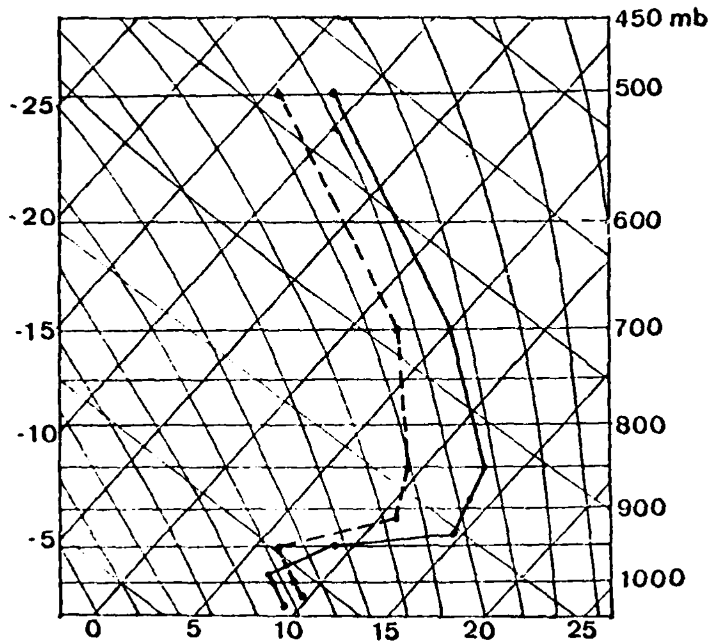
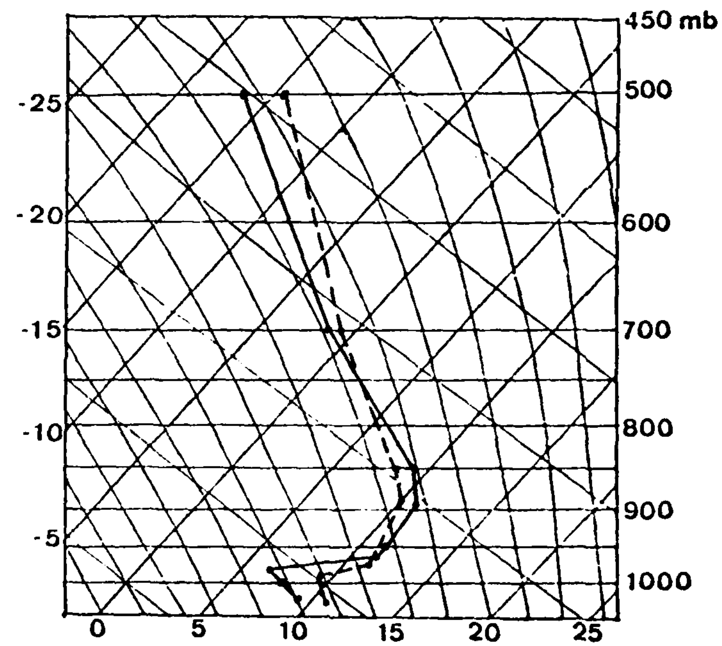


—— 9 July 1975

- - - 10 July 1975



—— 11 July 1975

- - - 12 July 1975

(DOD)

USAF SKEW T, log p DIAGRAM

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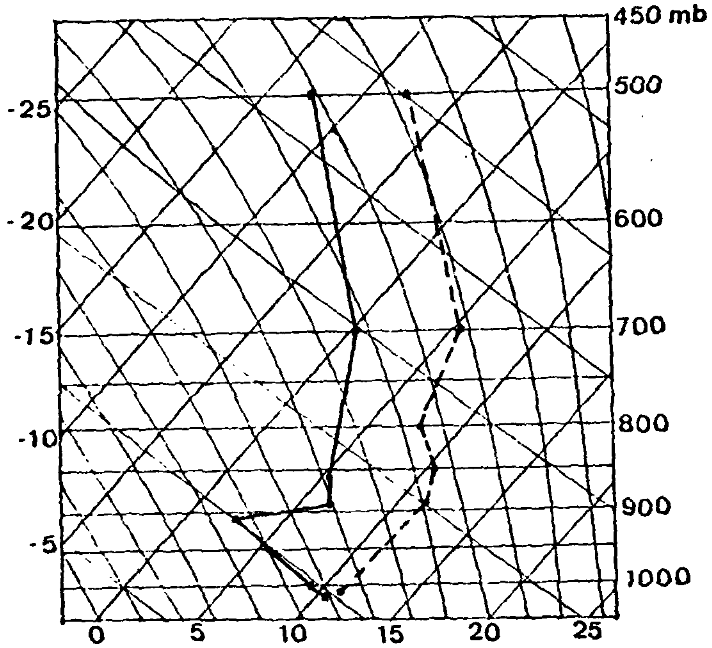
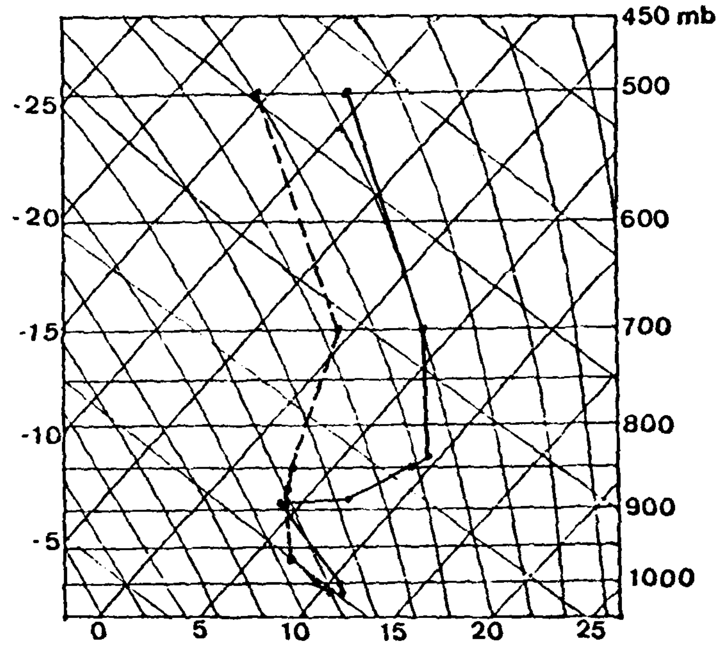


—— 14 July 1975

- - - 15 July 1975



—— 16 July 1975

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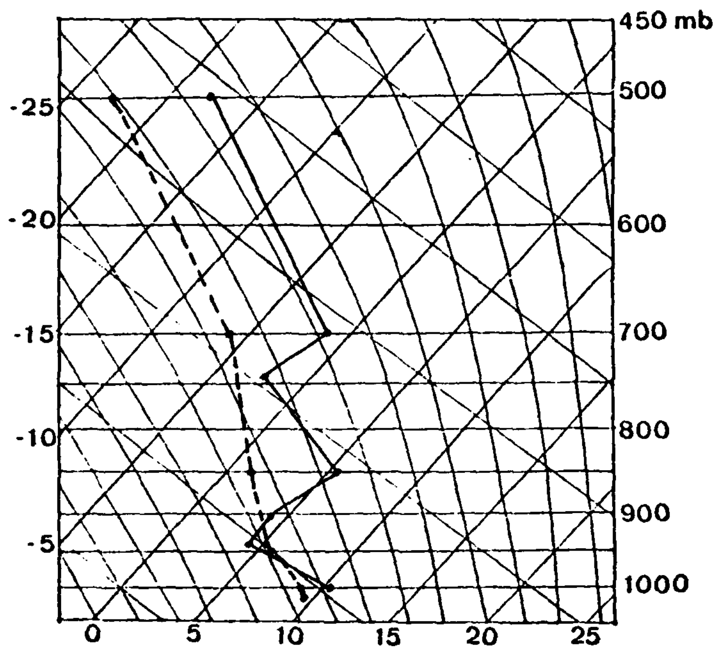
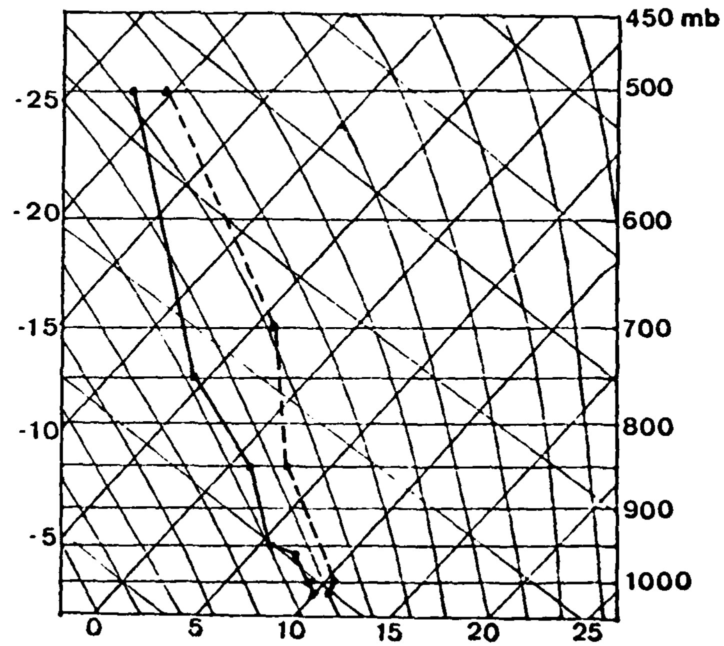


—— 18 July 1975

- - - 19 July 1975



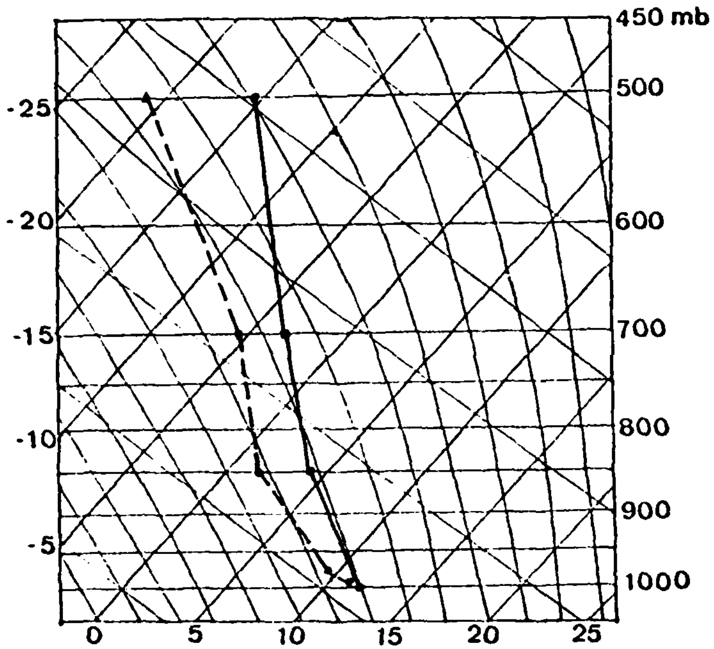
—— 20 July 1975

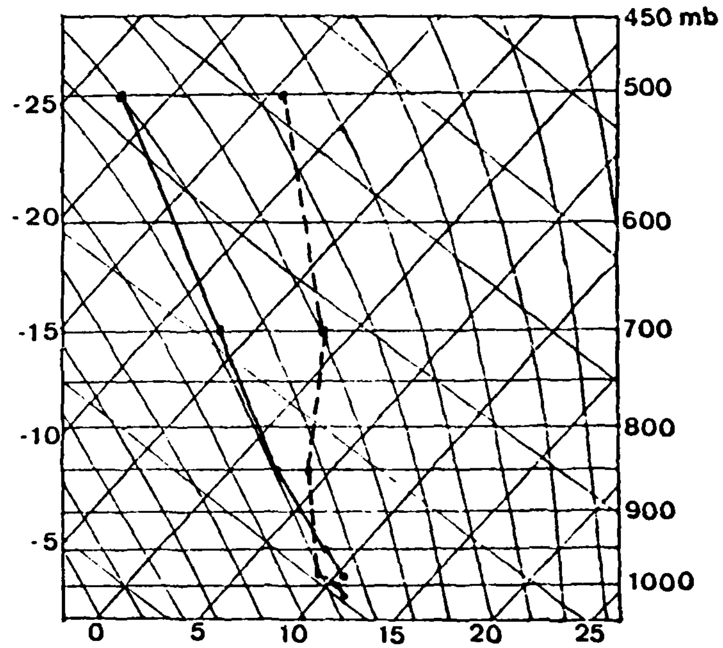
- - - 21 July 1975

(DOD)

USAF SKEW T, log p DIAGRAM

(SELECT PORTION)





——— 22 July 1975

- - - 23 July 1975

——— 24 July 1975

- - - 25 July 1975

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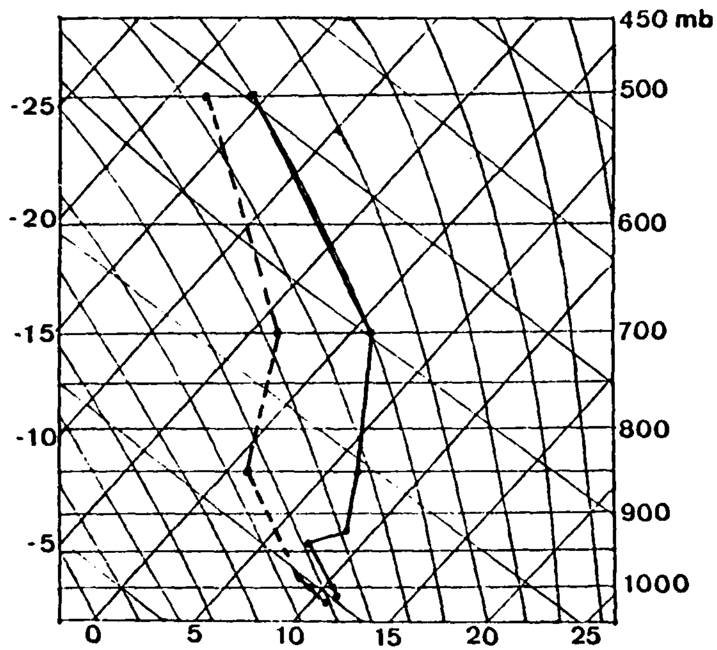
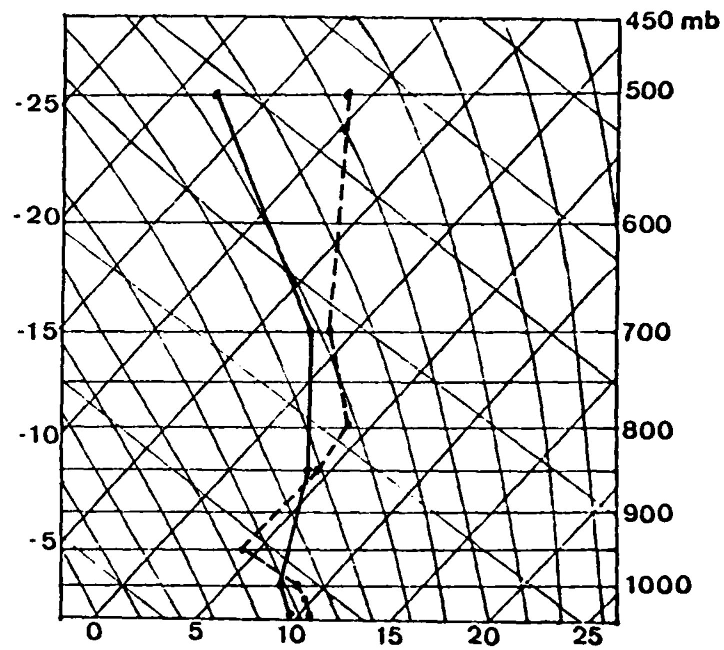


—— 26 July 1975

- - - 27 July 1975



—— 28 July 1975

- - - 29 July 1975

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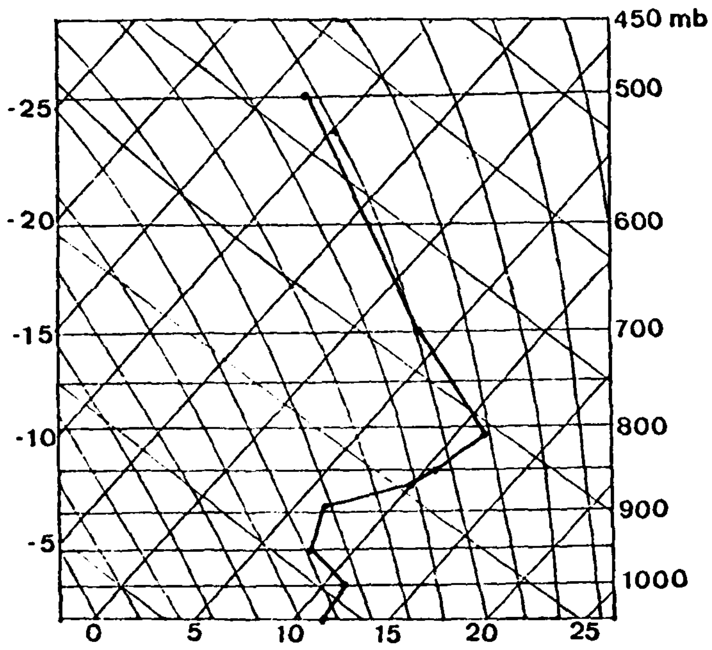
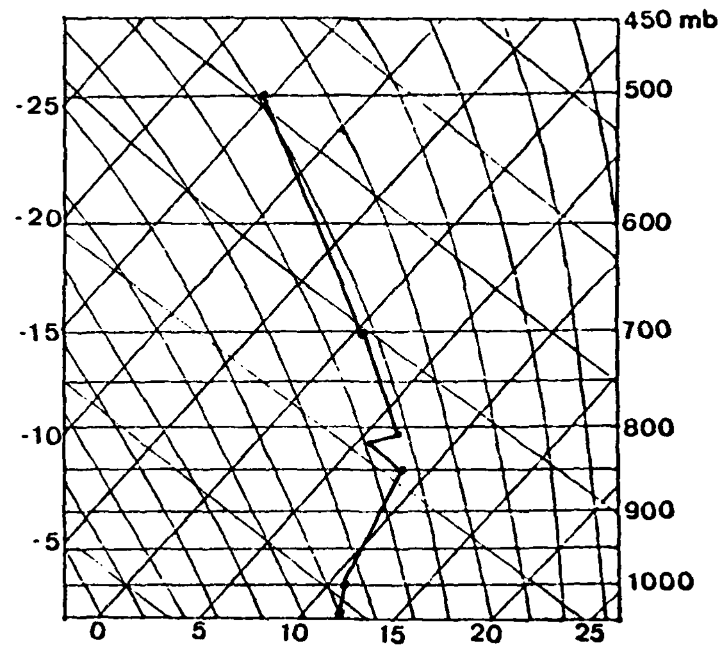


—— 30 July 1975



—— 31 July 1975

TABLES

TABLE I

SURFACE PRESSURE CHANGE

	PRE-FOG INTENSIFICATION			POST-FOG DISSIPATION		
CASE	DAYS	INCREASE IN mb	RATE/DAY	DAYS	DECREASE IN mb	RATE/DAY
1	3.5	15	4.3	2	6	-3
2	1	7	7	1.5	10	-6.7
3	2	13	6.5	1	7	-7
4	0.5	1	2	0.5	1	-2
5	5	8	1.6	2.5	14	-5.6
6	2	22	11	1	4	-4
7	2.5	8	3.2	3	21	-7
8	3.5	18	5.1	1.5	5	-3.3
AVERAGE	2.5	11.5	4.6 mb	1.6	8.4	-5.2 mb

TABLE II

DEW POINT TEMPERATURE CHANGE

CASE	PRE-FOG INTENSIFICATION			POST-FOG DISSIPATION		
	DAYS	INCREASE IN °C	RATE/DAY	DAYS	DECREASE IN °C	RATE/DAY
1	2.5	2.5	1	1.5	1.5	- 1
2	4.5	5.5	1.2	3.5	6.5	-1.9
3	1	2.5	2.5	2	5	- 2.5
4	2	4	2	1	6	- 6
5	2	4	2	1.5	1	- 0.67
6	3	2	0.67	2	3.5	-1.75
7	1.5	3.5	2.3	0.5	1	- 2
8	1	1.5	1.5	0.5	1	- 2
AVERAGE	2.2	3.2	1.5 °C	1.7	3.2	-1.9 °C

TABLE III

SUMMARY OF THE NON - FRONTAL FOG CASES.

CASE	YEAR	MONTH	START DAY/HOUR	DURATION IN HOURS
1	73	JUL	25/00Z	12
2[a]	77	JUL	13/00Z	24
3	73	AUG	5/00Z	48
4	73	AUG	10/12Z	48
5	73	AUG	20/12Z	12
6	77	AUG	12/00Z	48
7	77	AUG	16/12Z	108
8[b]	77	AUG	26/12Z	12

a) Does not fit open ocean model
b) Does not develop past Stage I of model

1) Total Non-frontal Fog Duration - 312 Hours
2) Total Advection Fog Duration - 276 Hours
3) Average Non-Frontal Fog Duration - 39 Hours
4) Average Advection Fog Duration - 46 Hours

TABLE IV

LIMITING INDICES FOR EACH FOG CASE.

	1	2	3	4	5	6	7	8
UNFAVORABLE INDICES FOR THE 24 HOUR PRE-FOG PERIOD	INV HT	DIFFERENT MODEL DEVELOPMENT	MOIST INDEX	INV HT TEMP AND MOIST INDEX	INV HT TEMP AND MOIST INDEX	INV HT TEMP INDEX	INV HT WIND DIRECT	INV HT TEMP AND MOIST INDEX
UNFAVORABLE INDICES FOR THE 24 HOUR POST-FOG PERIOD	INV HT MOIST INDEX		TEMP AND MOIST INDEX	INV HT TEMP AND MOIST INDEX	INV HT TEMP AND MOIST INDEX		INV HT WIND DIRECT	INV HT TEMP AND MOIST INDEX

FIGURES

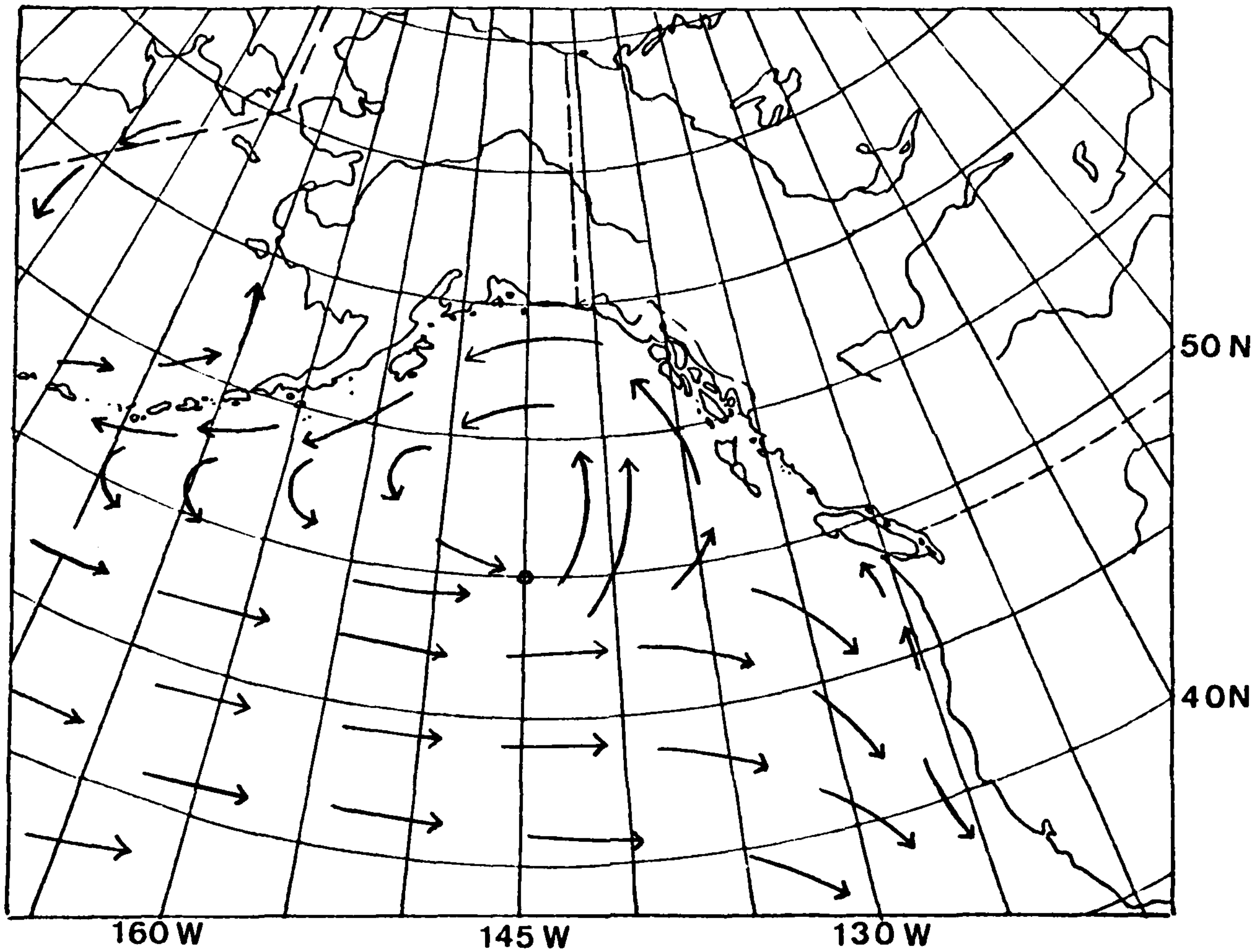


Figure 1. Ocean Station Papa (50N,145W) and General Sea Surface Circulation

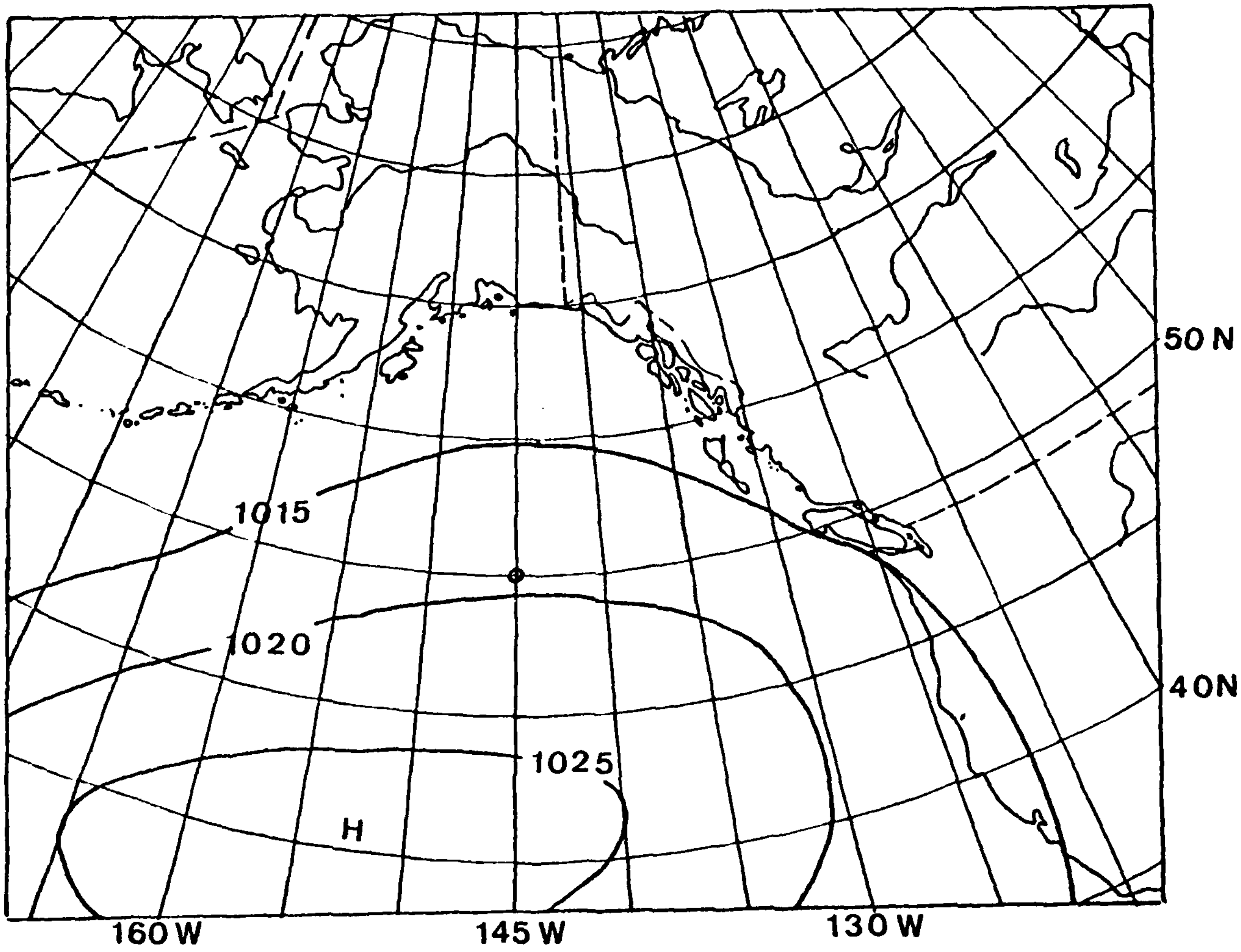


Figure 2. Mean Sea Level Pressure in July (mb)
Hourwitz and Austin (1944) - Climatology

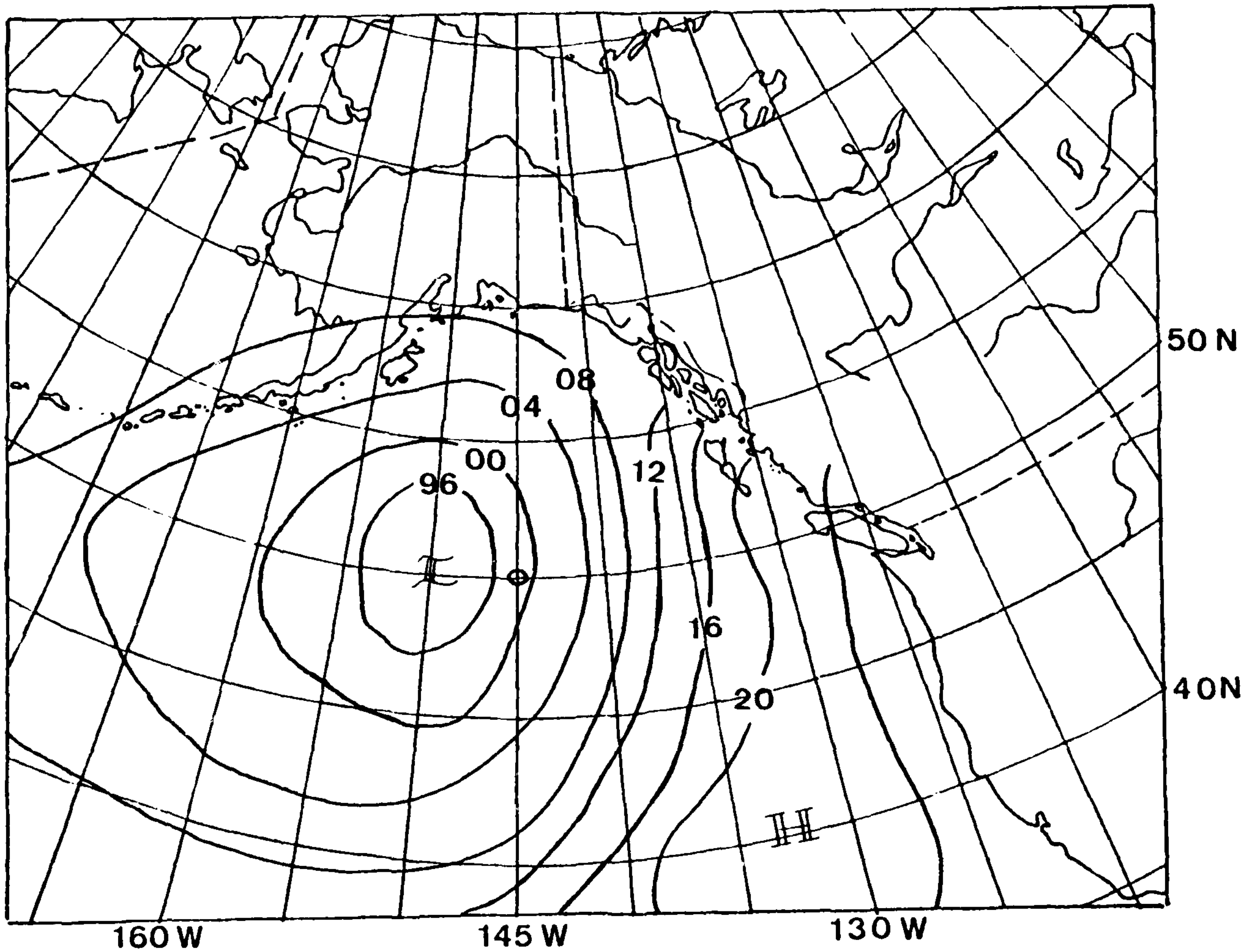


Figure 3. Surface Synoptic Display, 10 August 1977, 00Z

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AN OPEN-OCEAN MARINE FOG DEVELOPMENT AND FORECAST MODEL FOR OCE--ETC(U)
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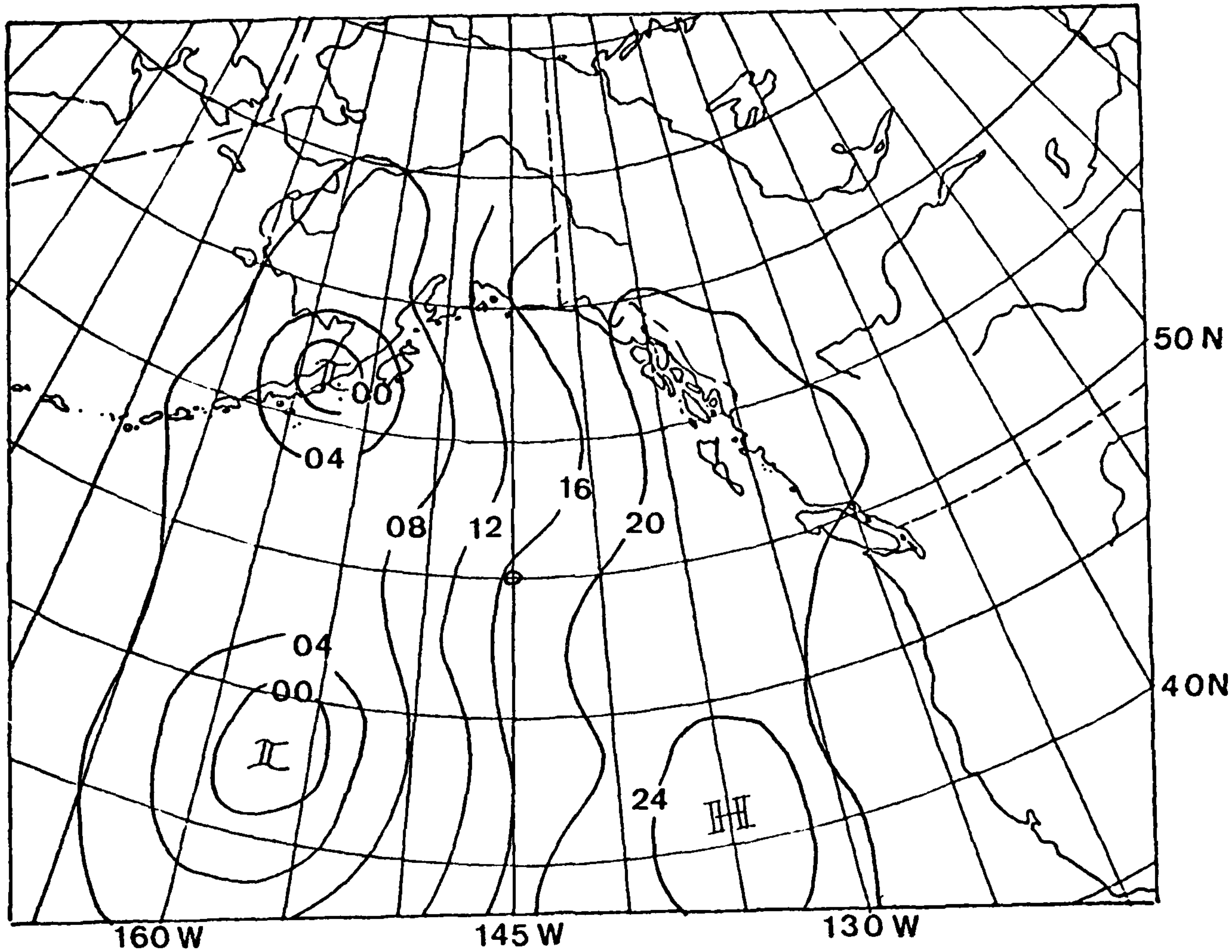


Figure 4. Surface Synoptic Display, 11 August 1977, 00Z

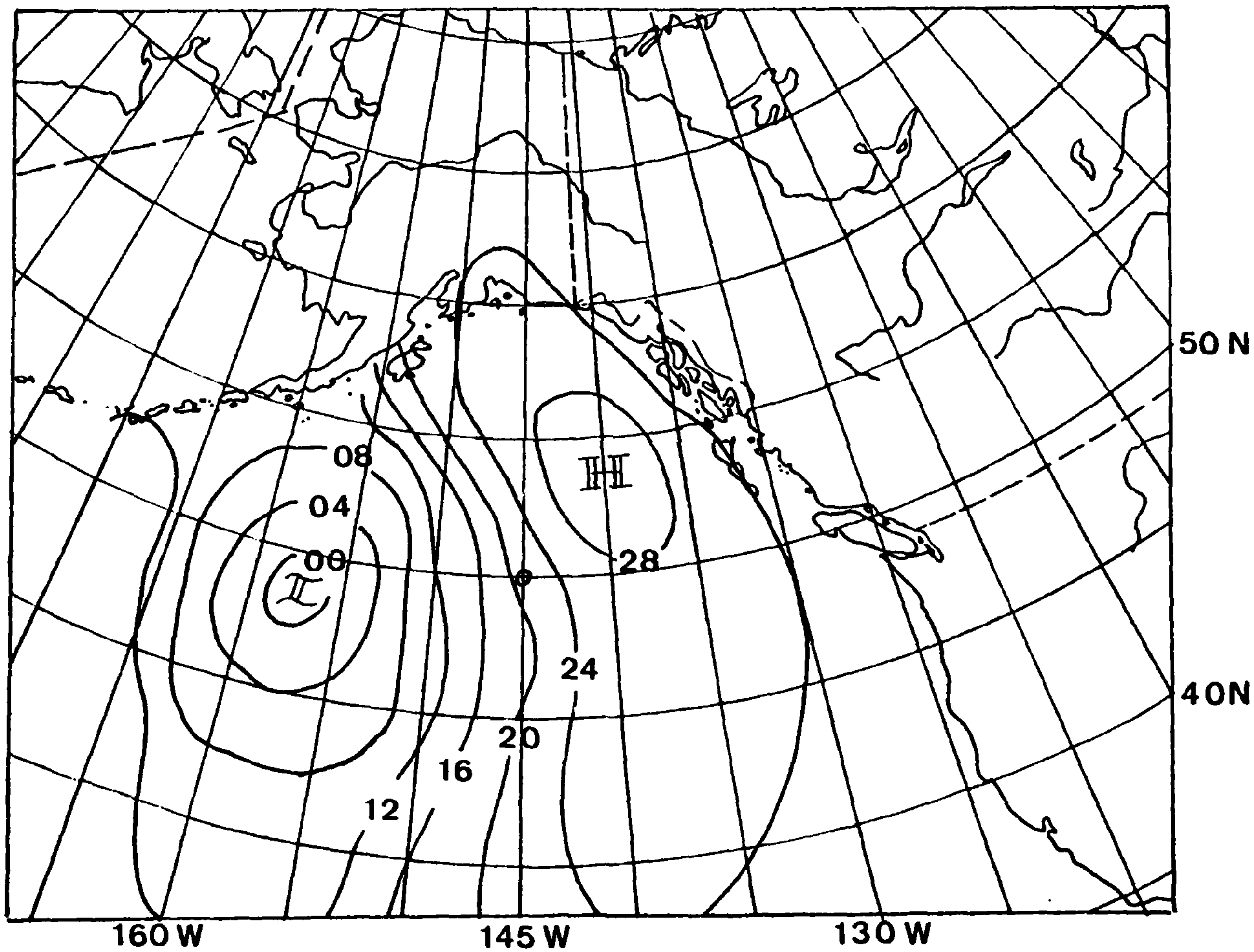


Figure 5. Surface Synoptic Display, 12 August 1977, 00Z

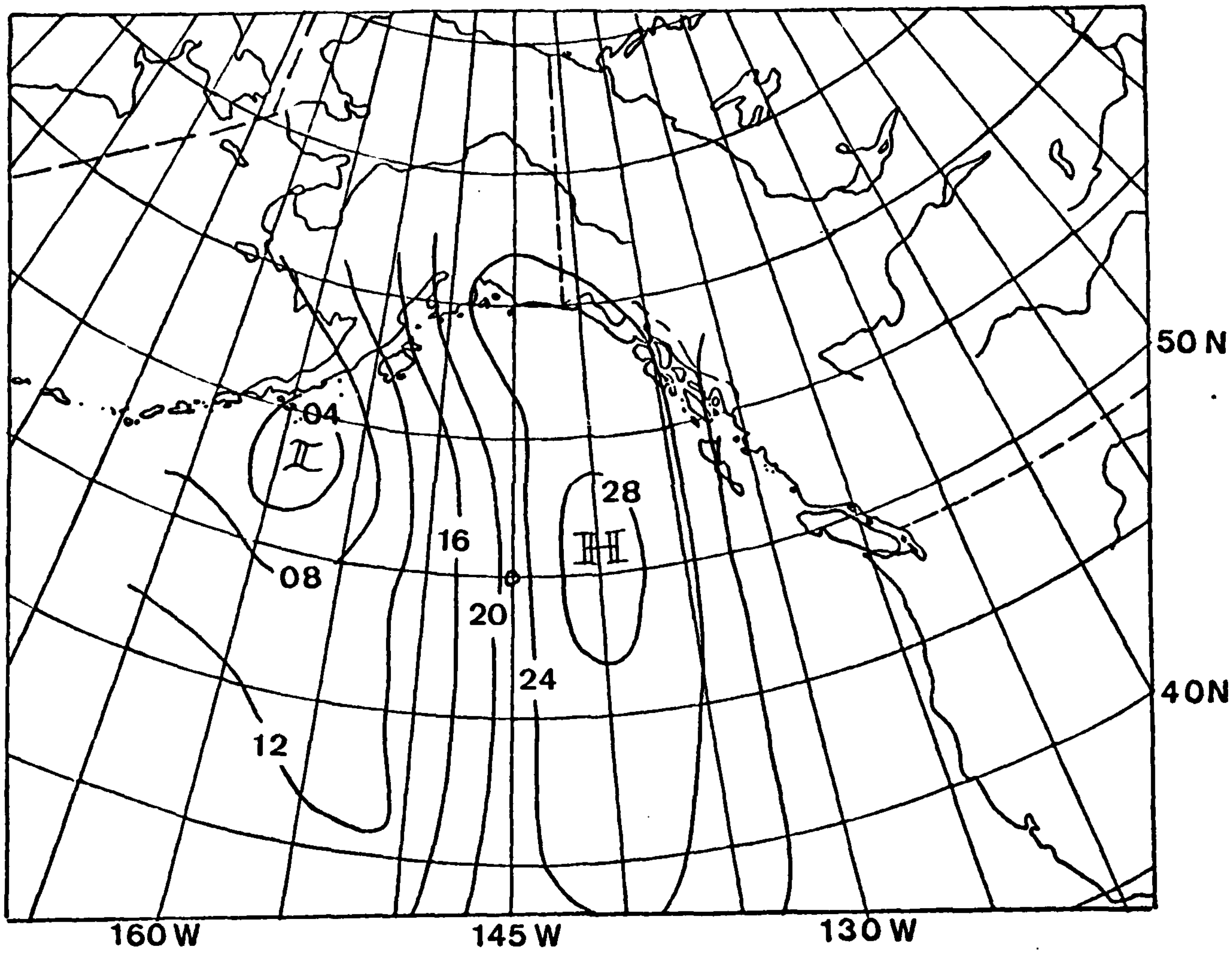


Figure 6. Surface Synoptic Display, 13 August 1977, 00Z

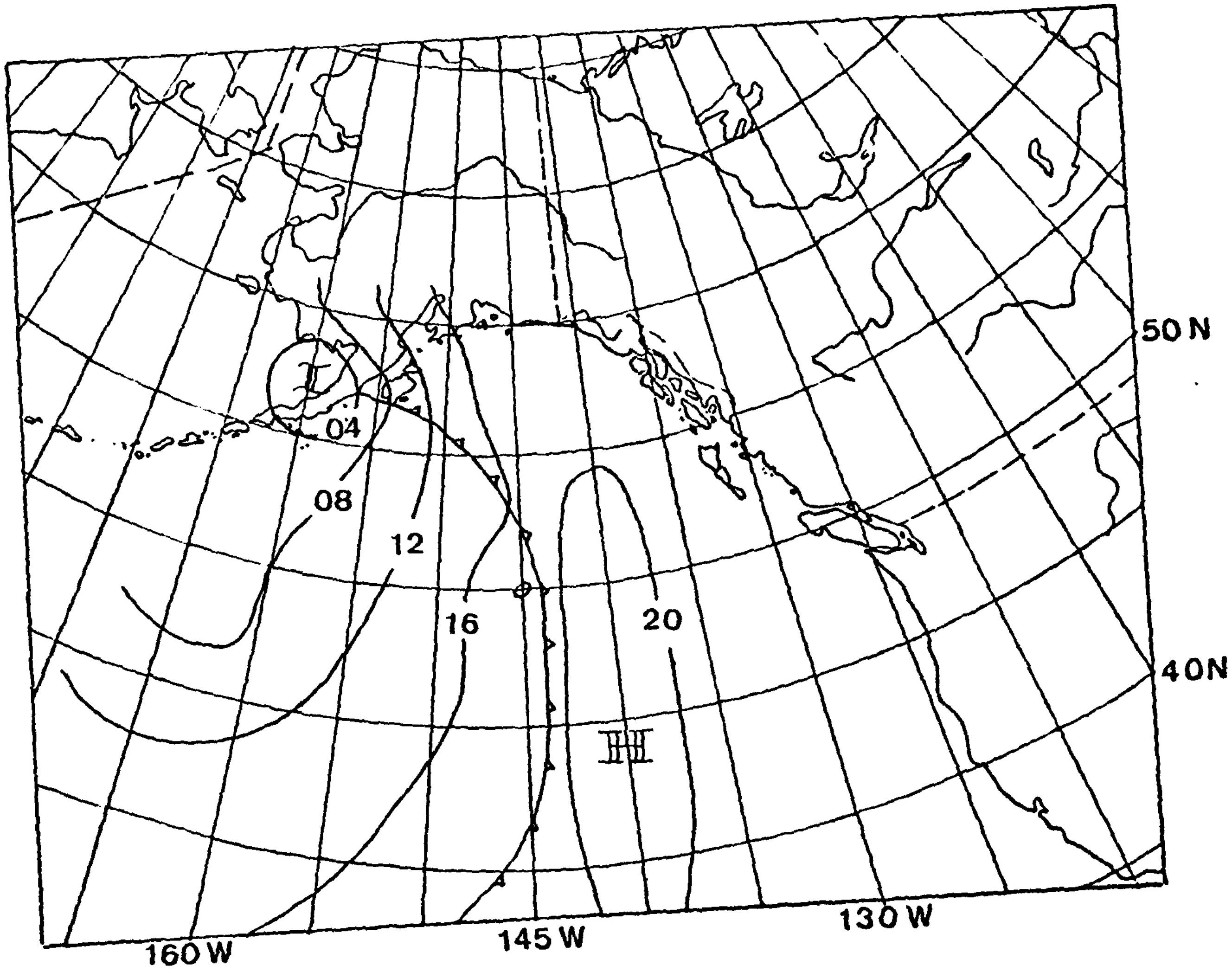


Figure 7. Surface Synoptic Display, 14 August 1977, 00Z

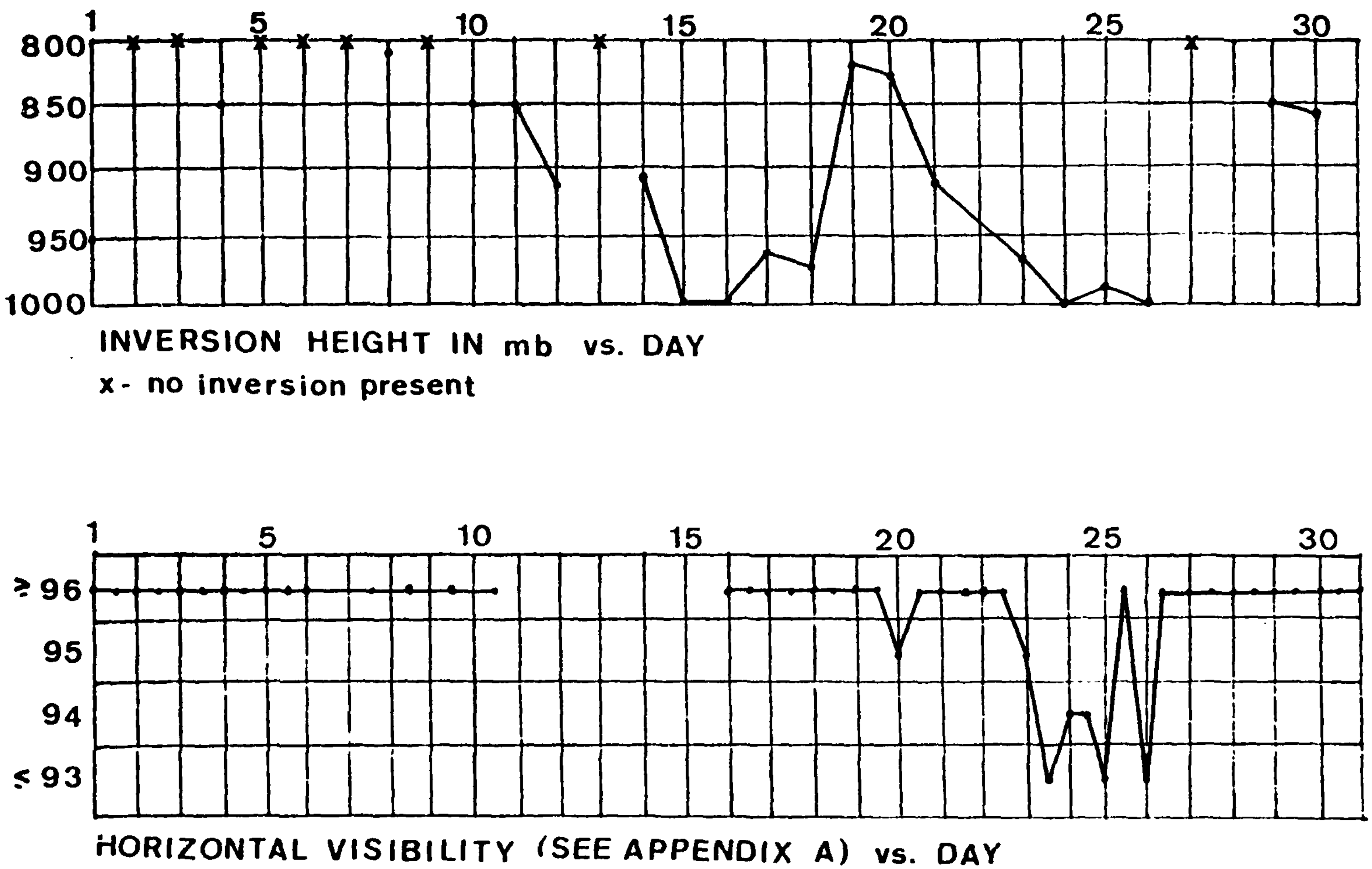


Figure 8. July 1973 Inversion Height and Horizontal Visibility

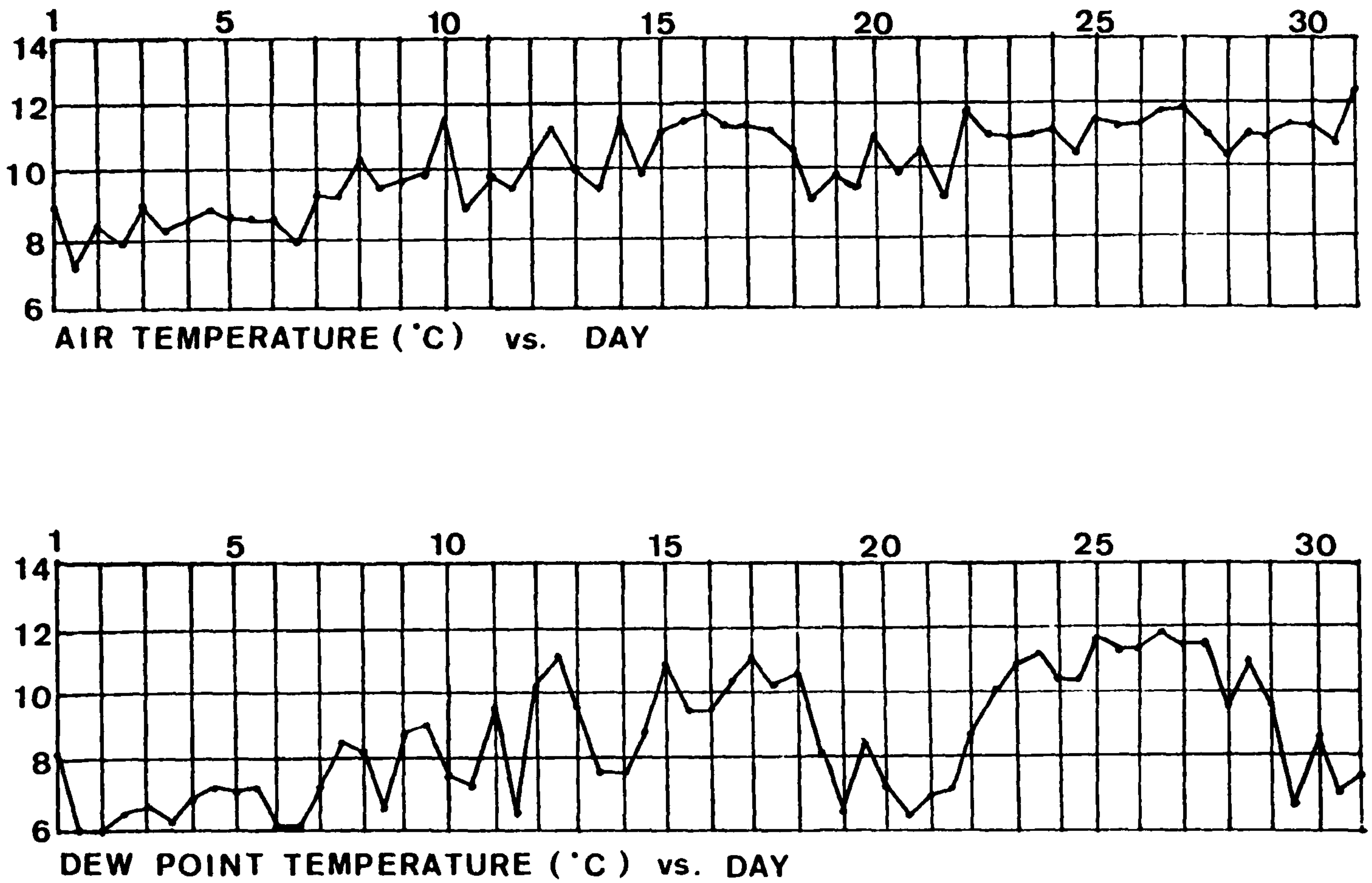


Figure 9. July 1973 Air Temperature and Dew Point Temperature

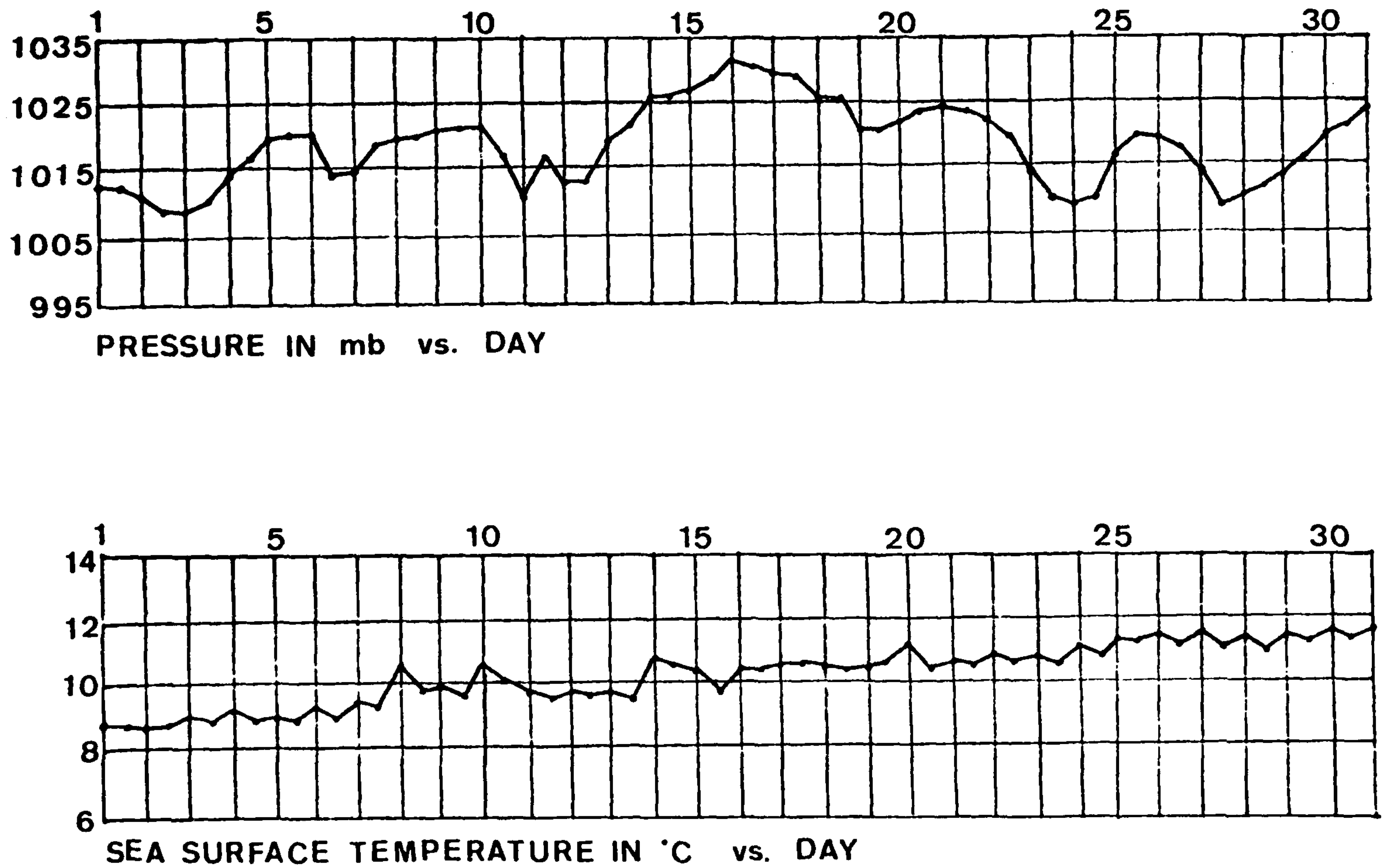


Figure 10. July 1973 Sea Level Press., and Sea Surface Temp.

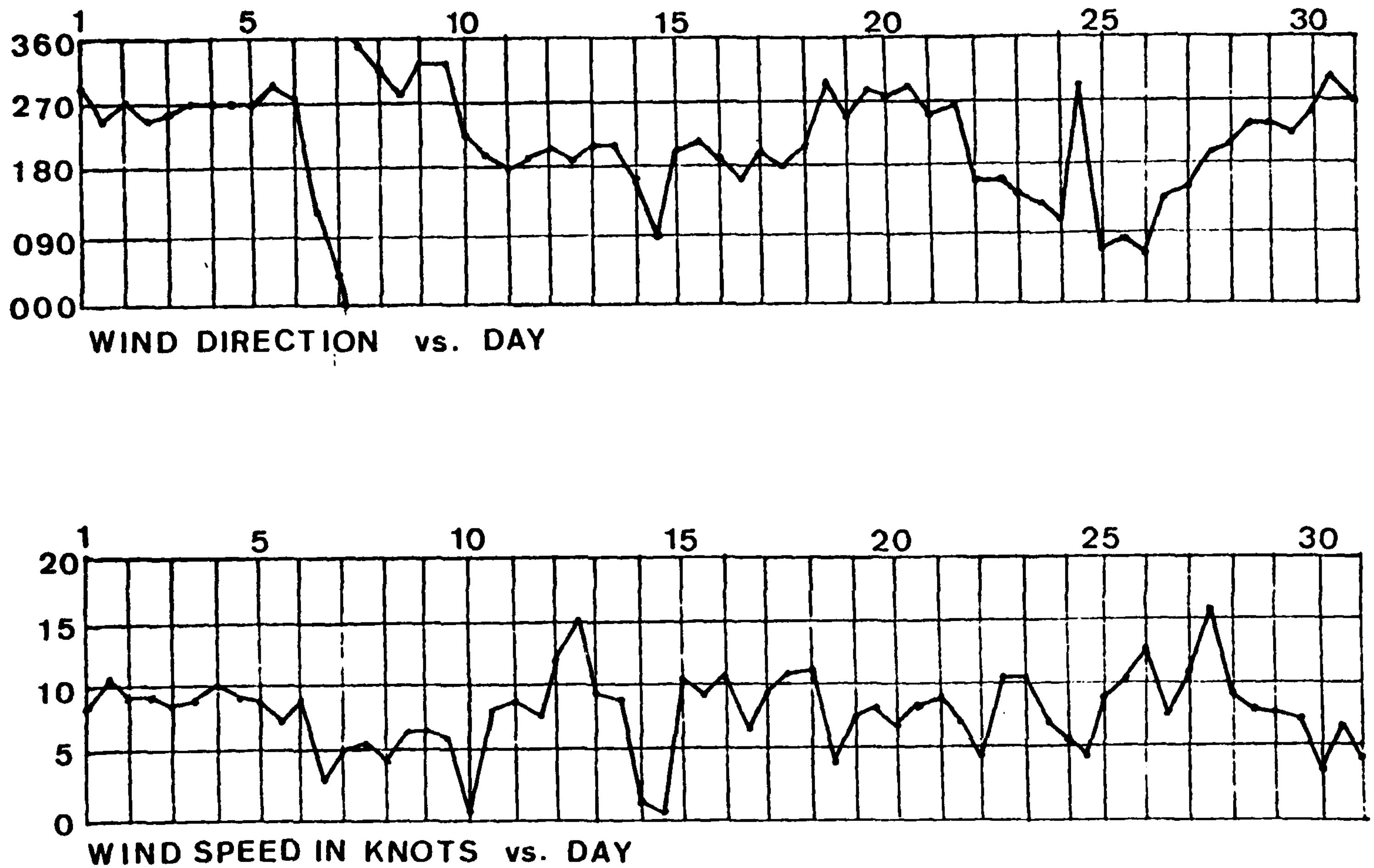


Figure 11. July 1973 Wind Direction and Wind Speed

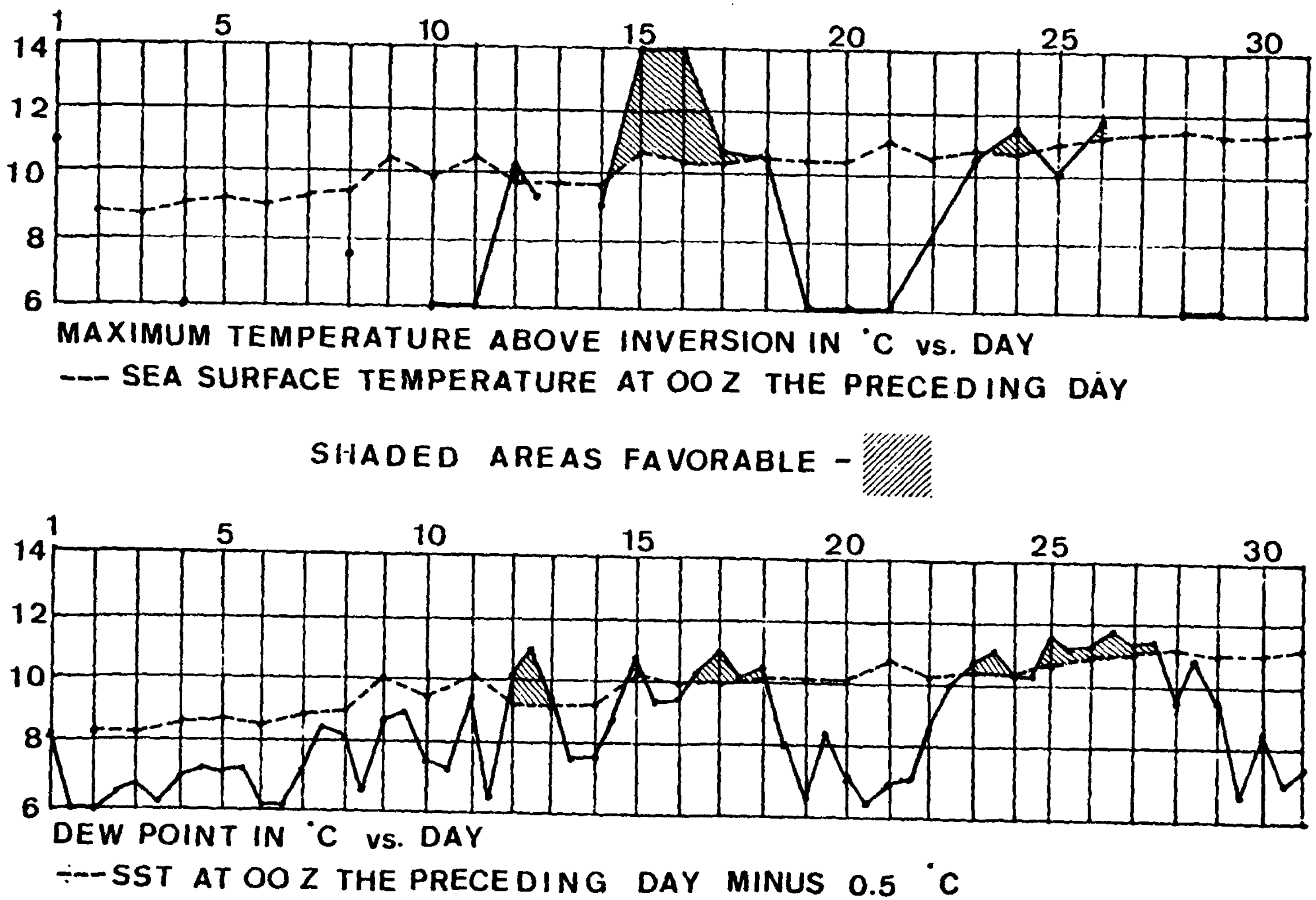


Figure 12. July 1973 Temp. Index and Moisture Index

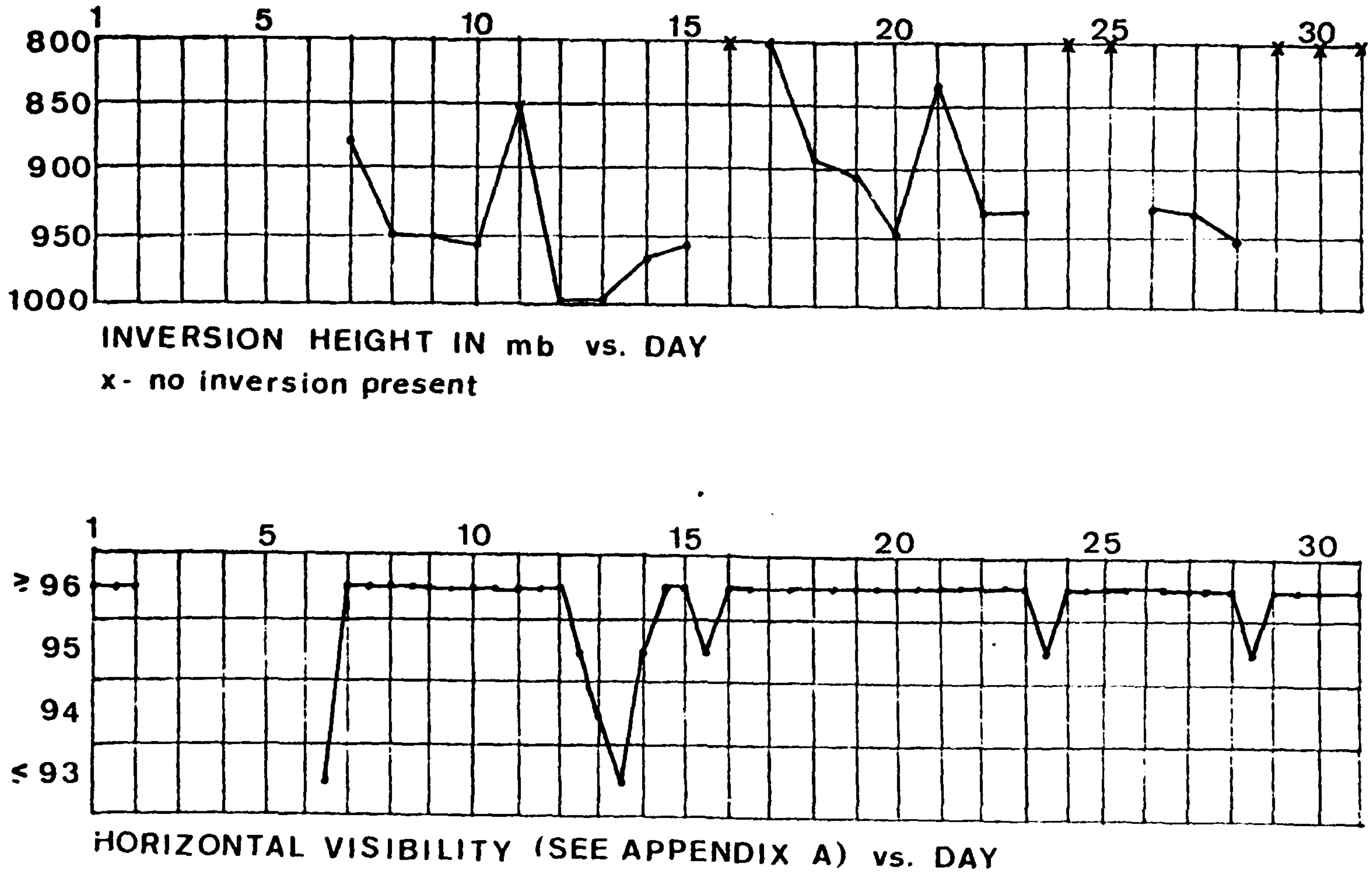


Figure 13. July 1977 Inversion Height and Horizontal Visibility

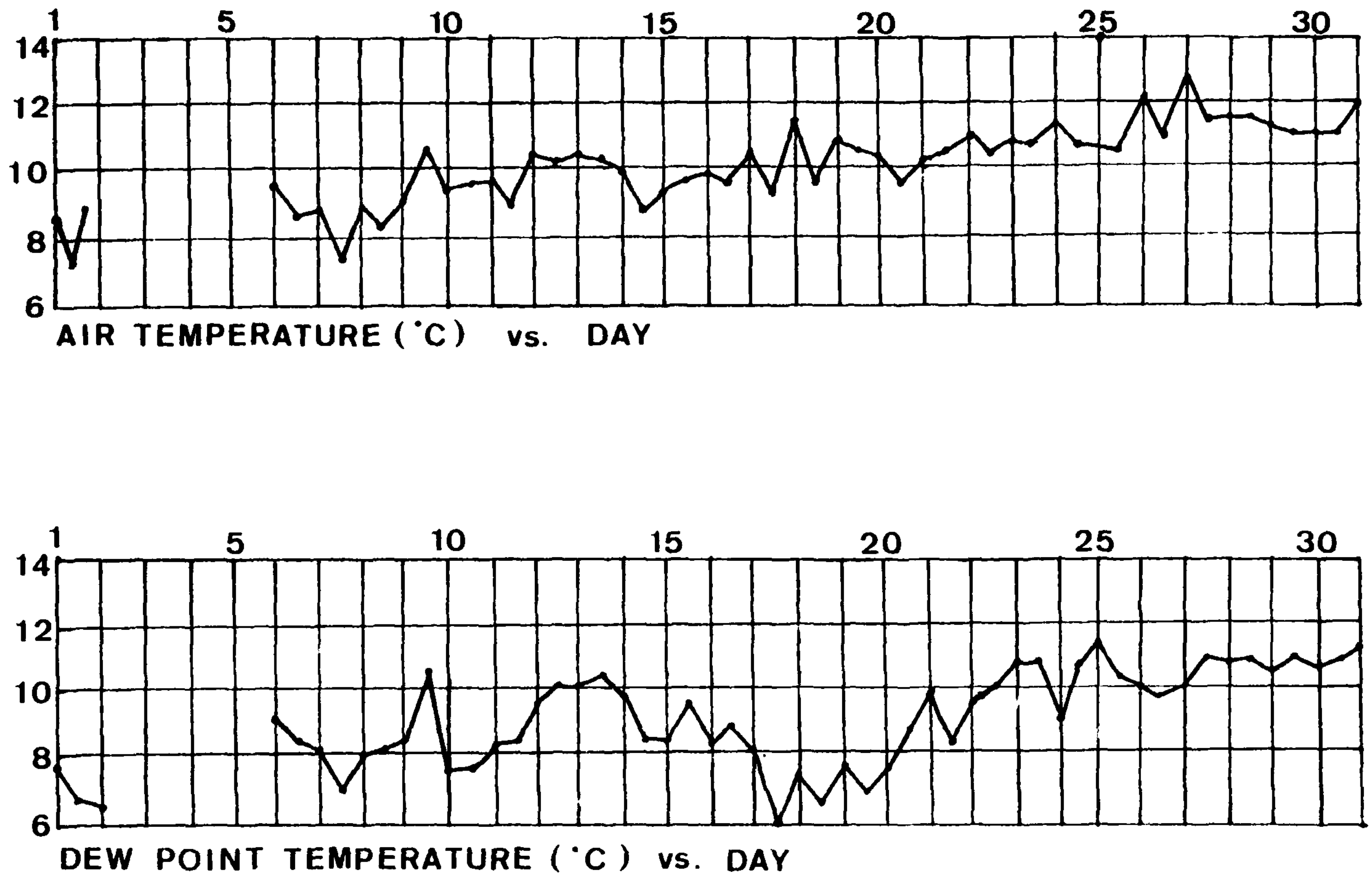


Figure 14. July 1977 Air Temperature and Dew Point Temperature

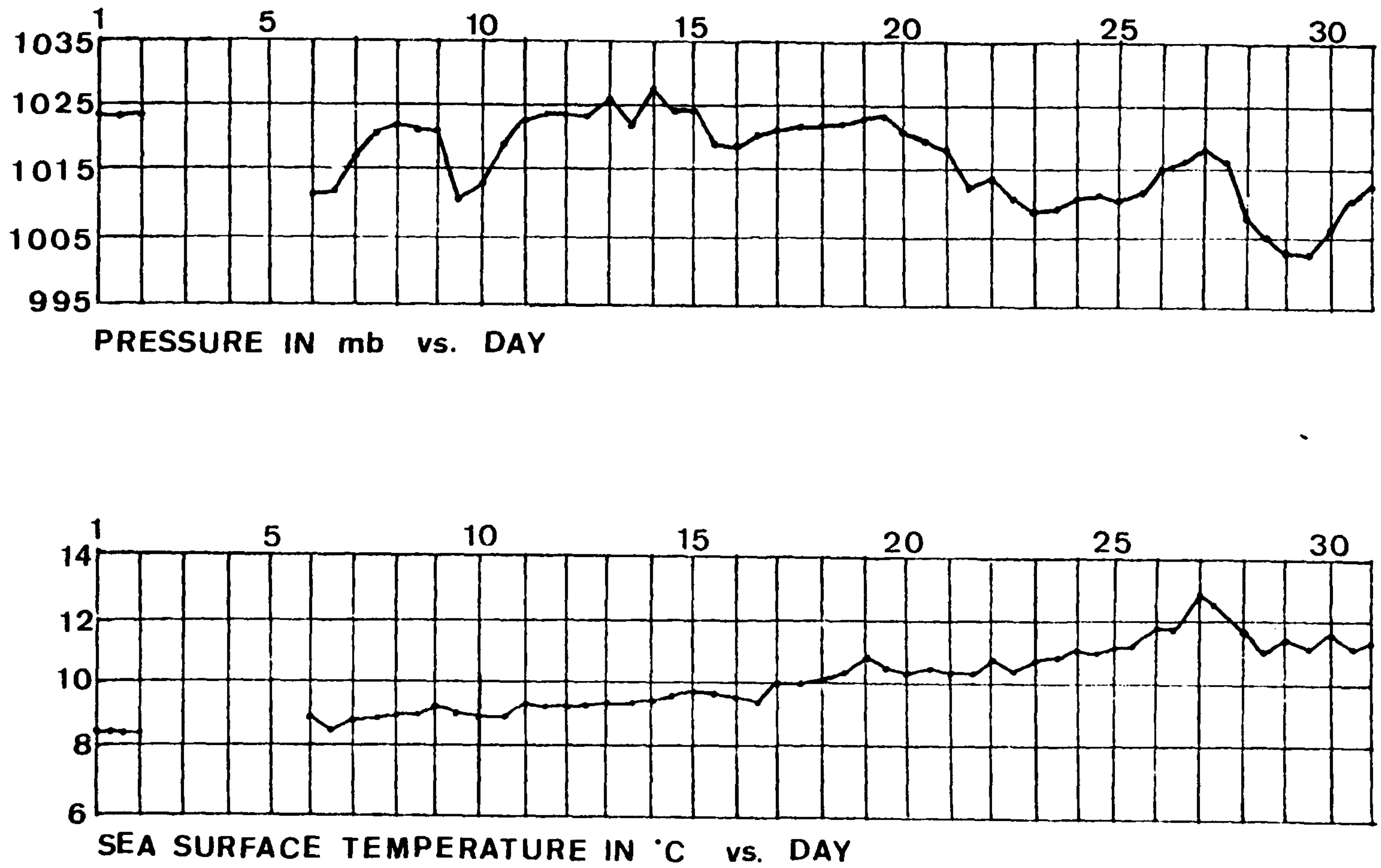


Figure 15. July 1977 Sea Level Pressure and Sea Surface Temperature

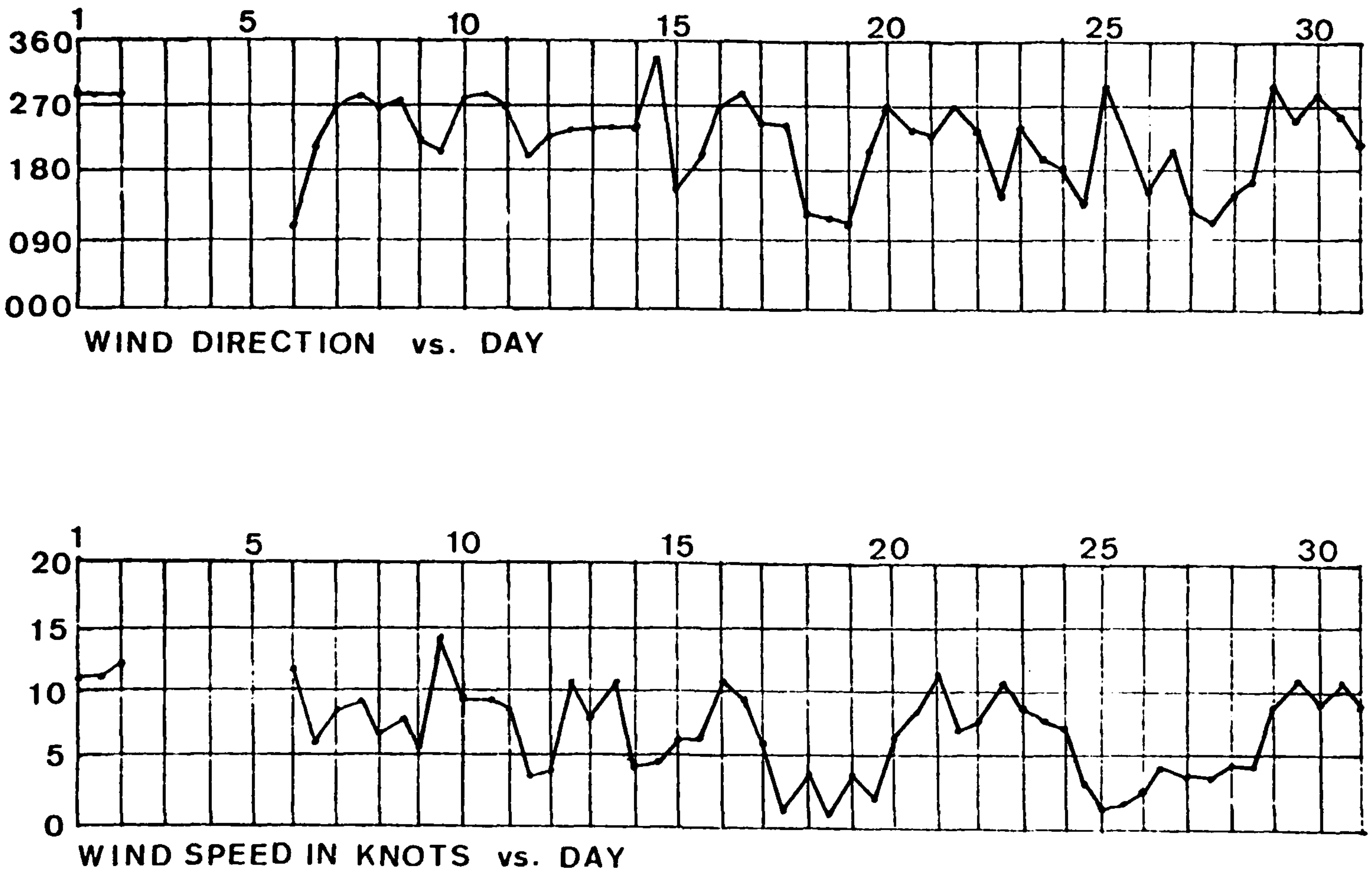


Figure 16. July 1977 Wind Direction and Wind Speed

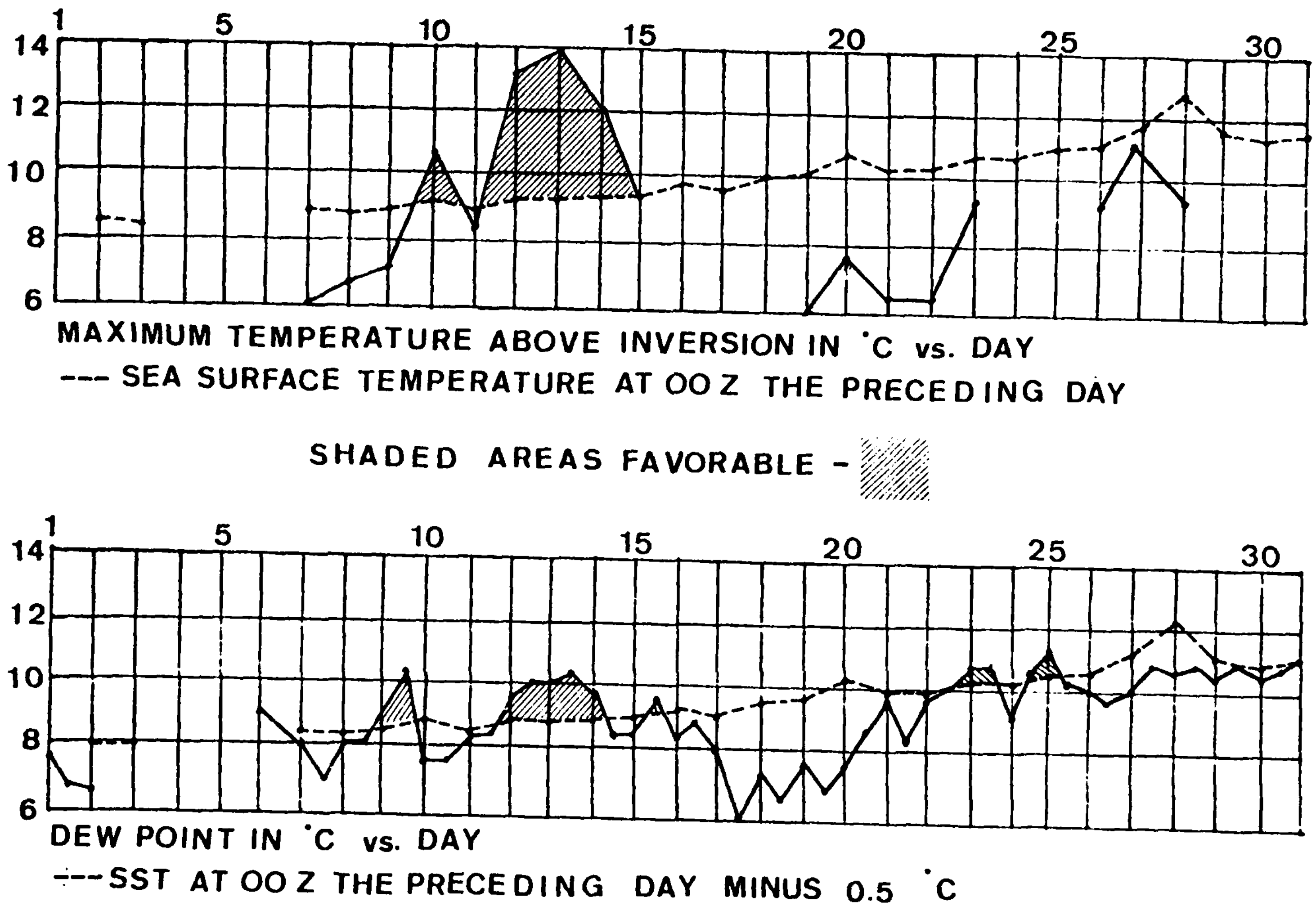


Figure 17. July 1977 Temperature Index and Moisture Index

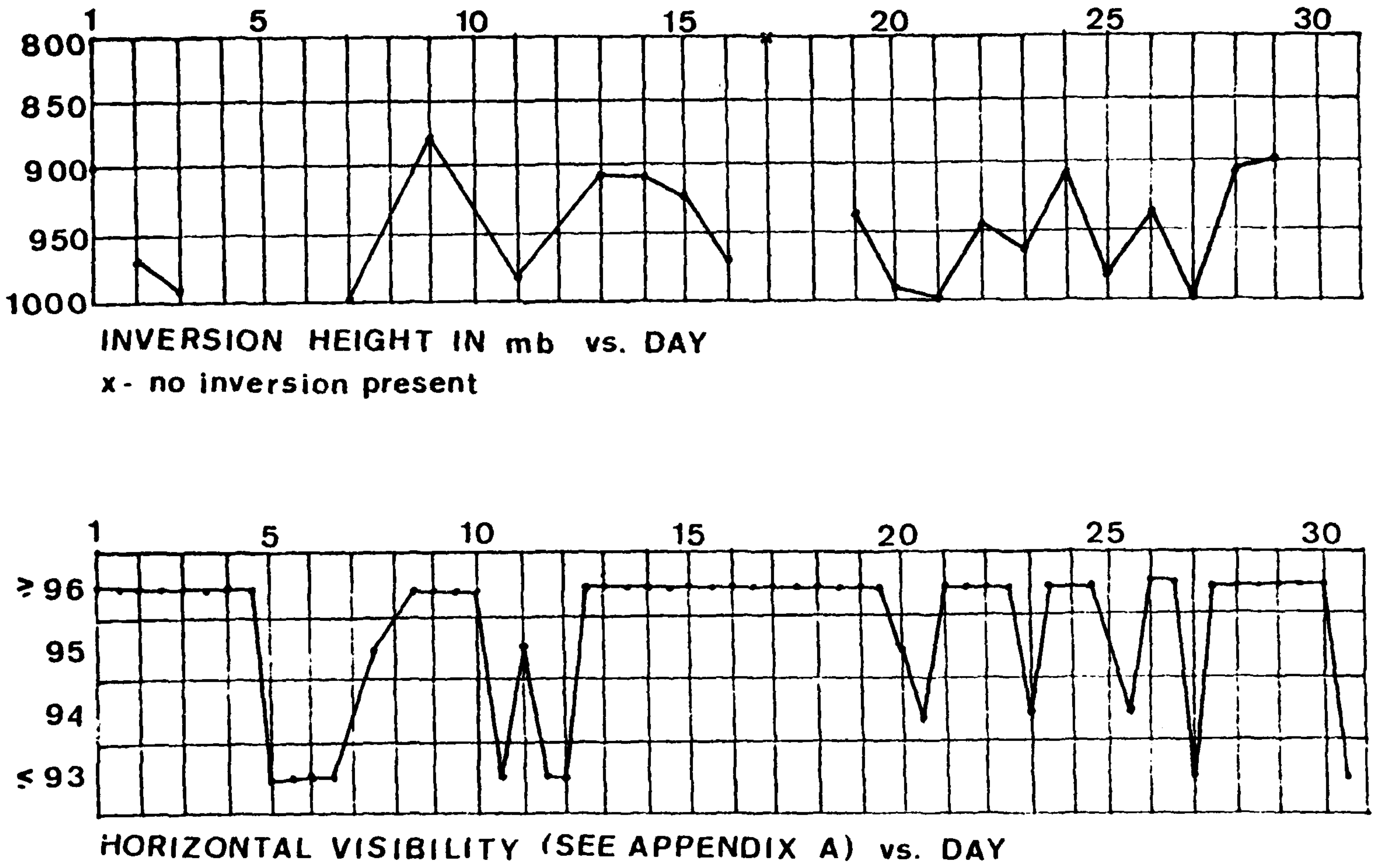


Figure 18. Aug. 1973 Inversion Height and Horizontal Visibility

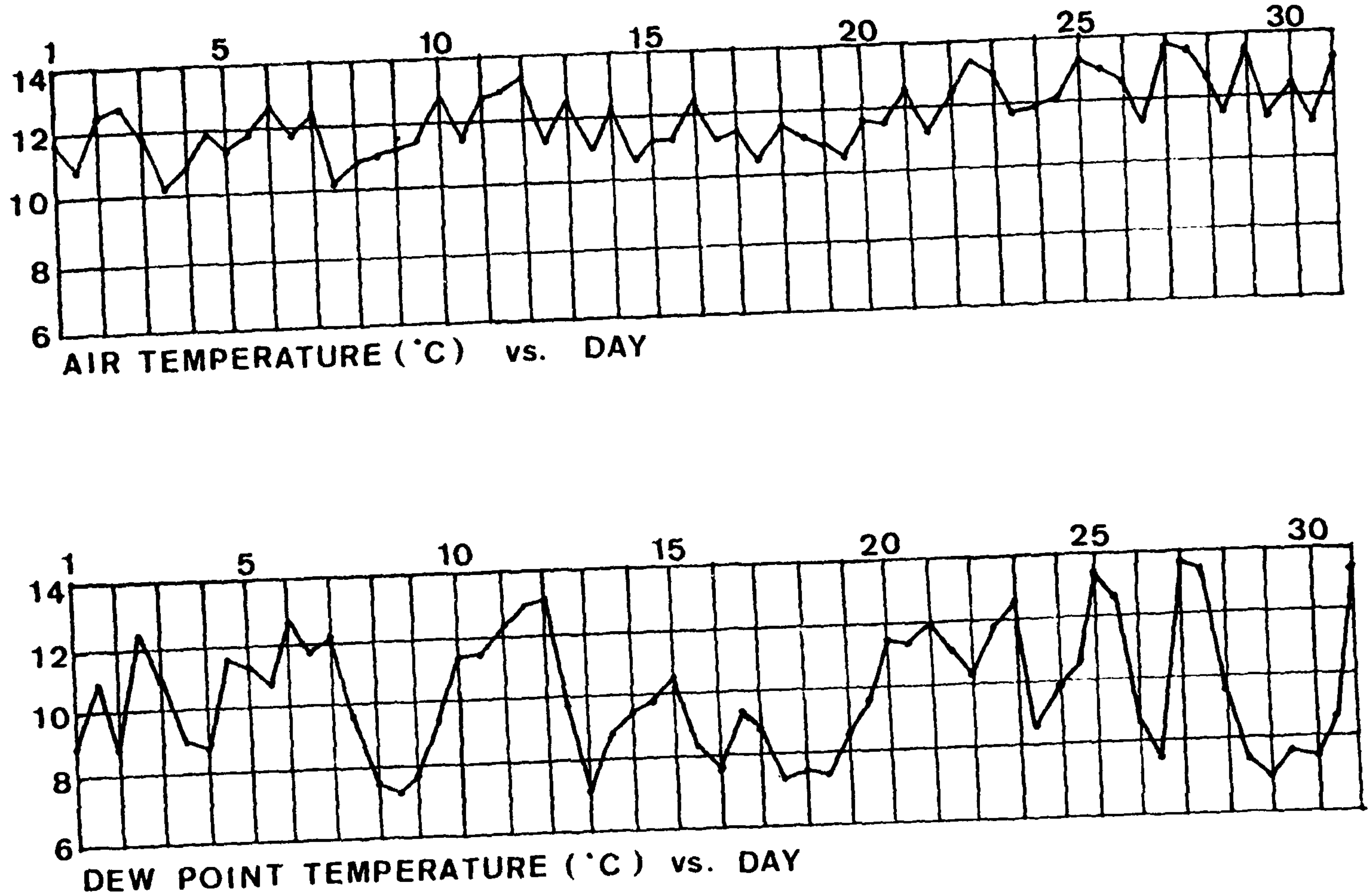


Figure 19. Aug.1973 Air Temperature and Dew Point Temperature

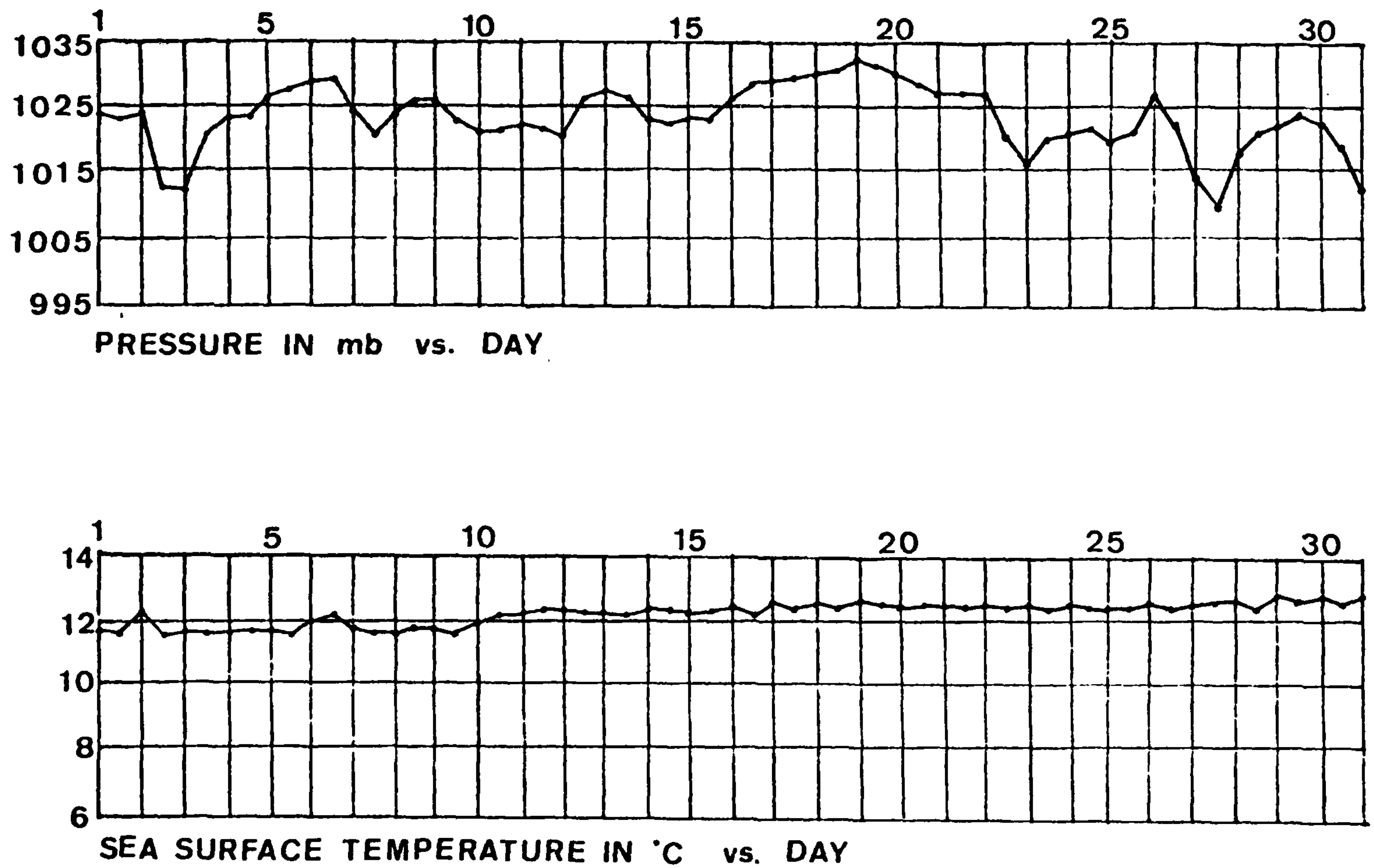


Figure 20. Aug. 1973 Sea Level Pressure and Sea Surface Temperature

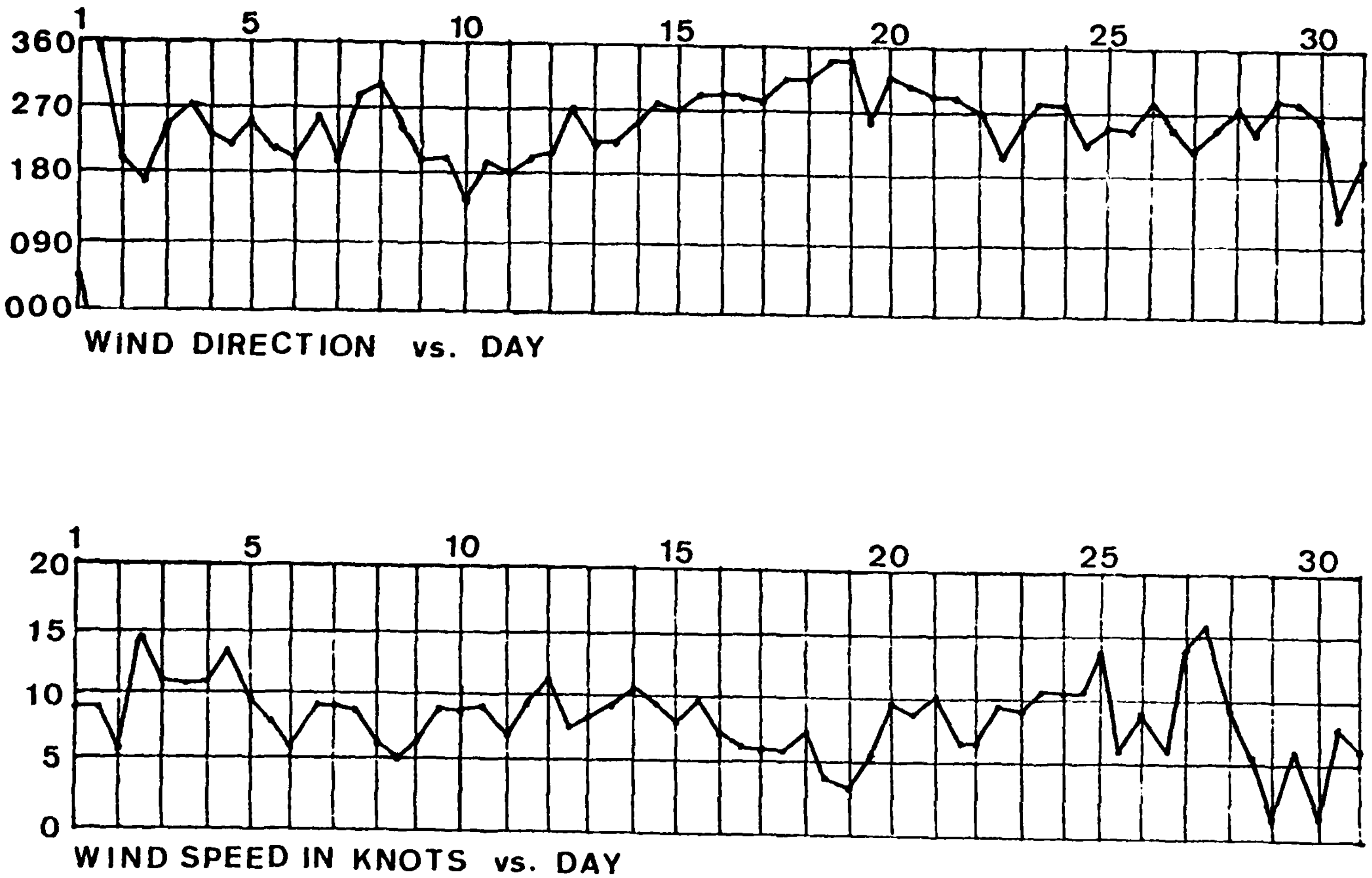


Figure 21. Aug. 1973 Wind Direction and Wind Speed

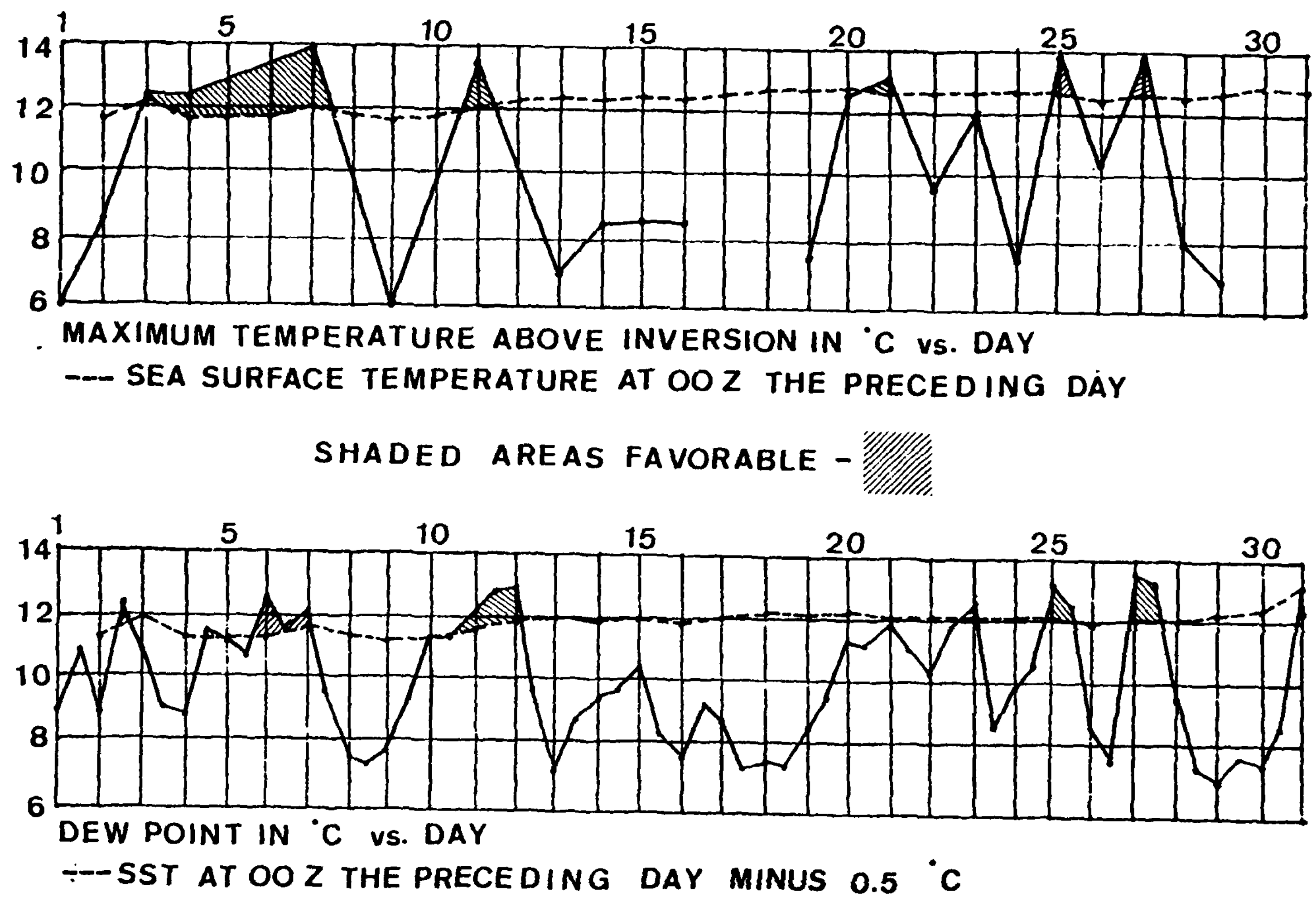


Figure 22. Aug. 1973 Temperature Index and Moisture Index

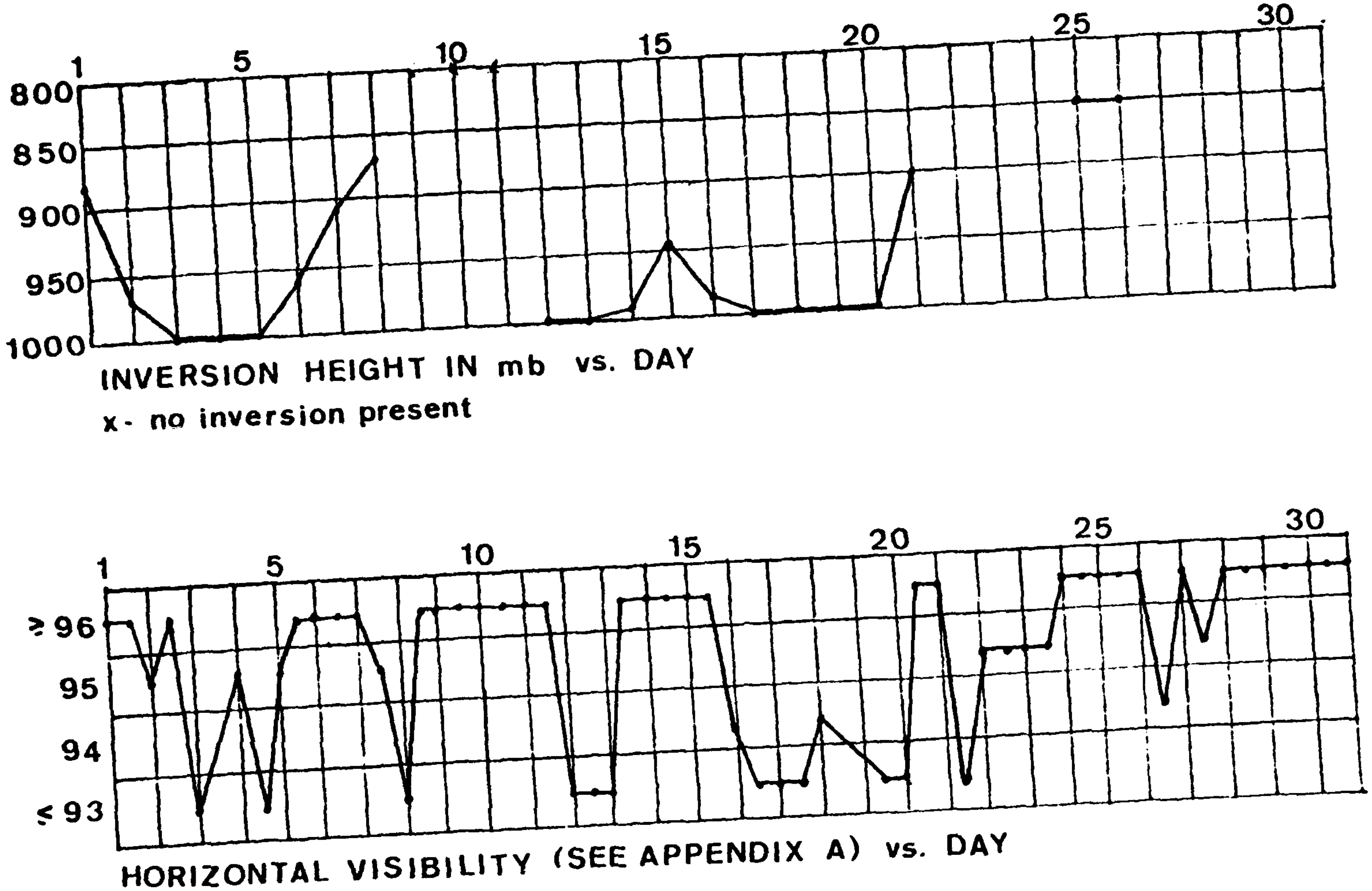


Figure 23. Aug. 1977 Inversion Height and Horizontal Visibility

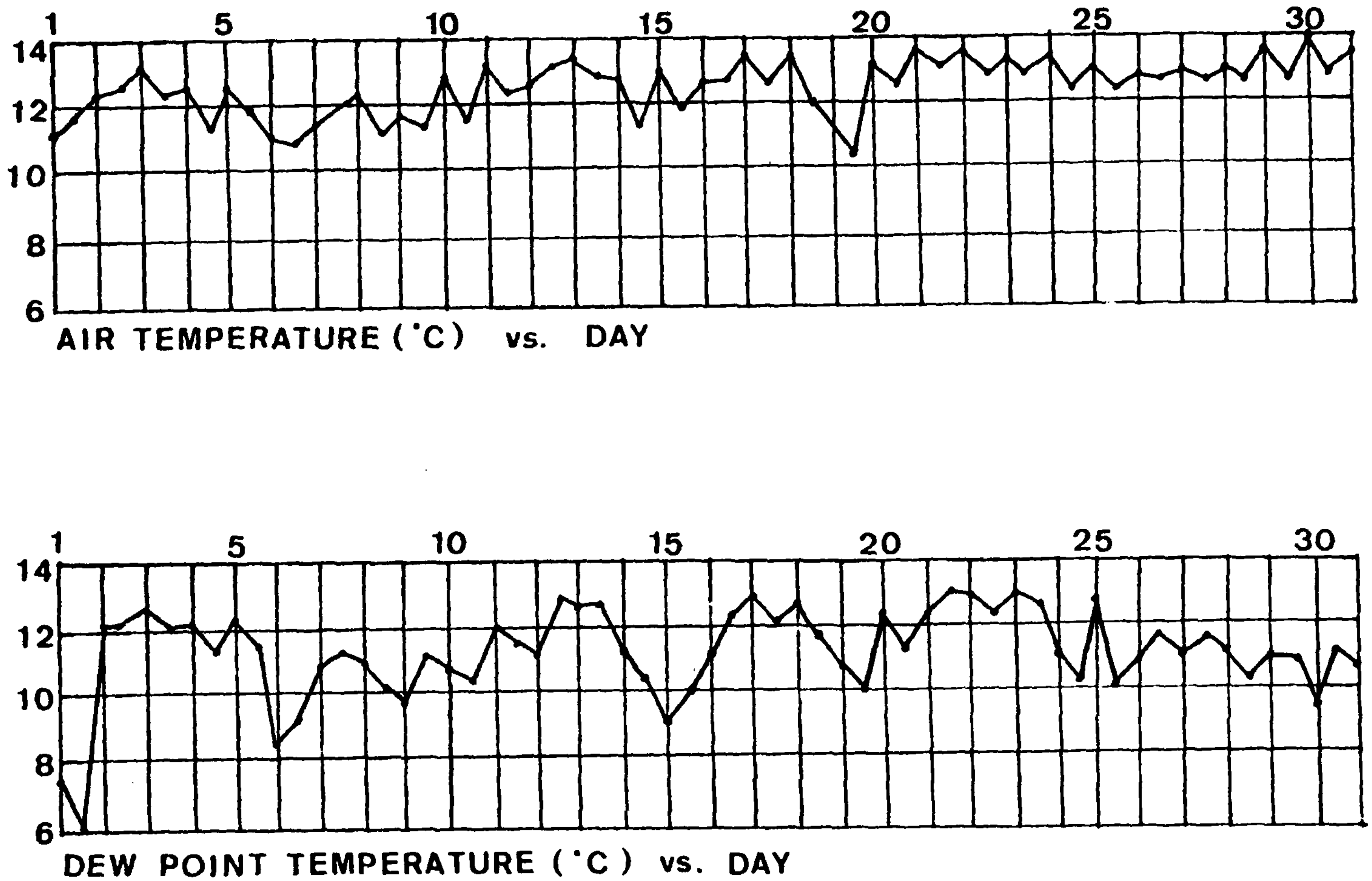


Figure 24. Aug. 1977 Air Temperature and Dew Point Temperature

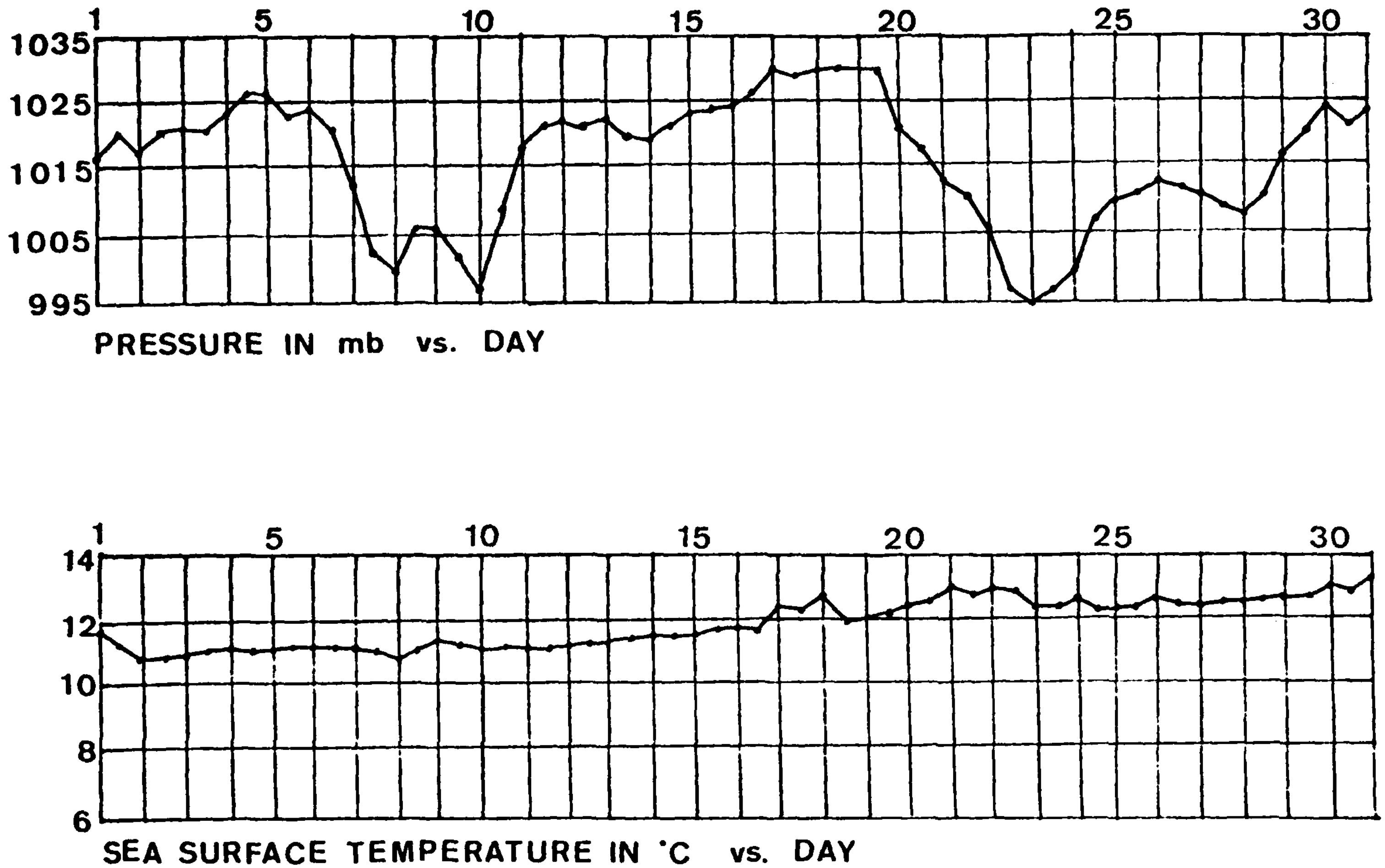


Figure 25. Aug.1977 Sea Level Pressure and Sea Surface Temperature

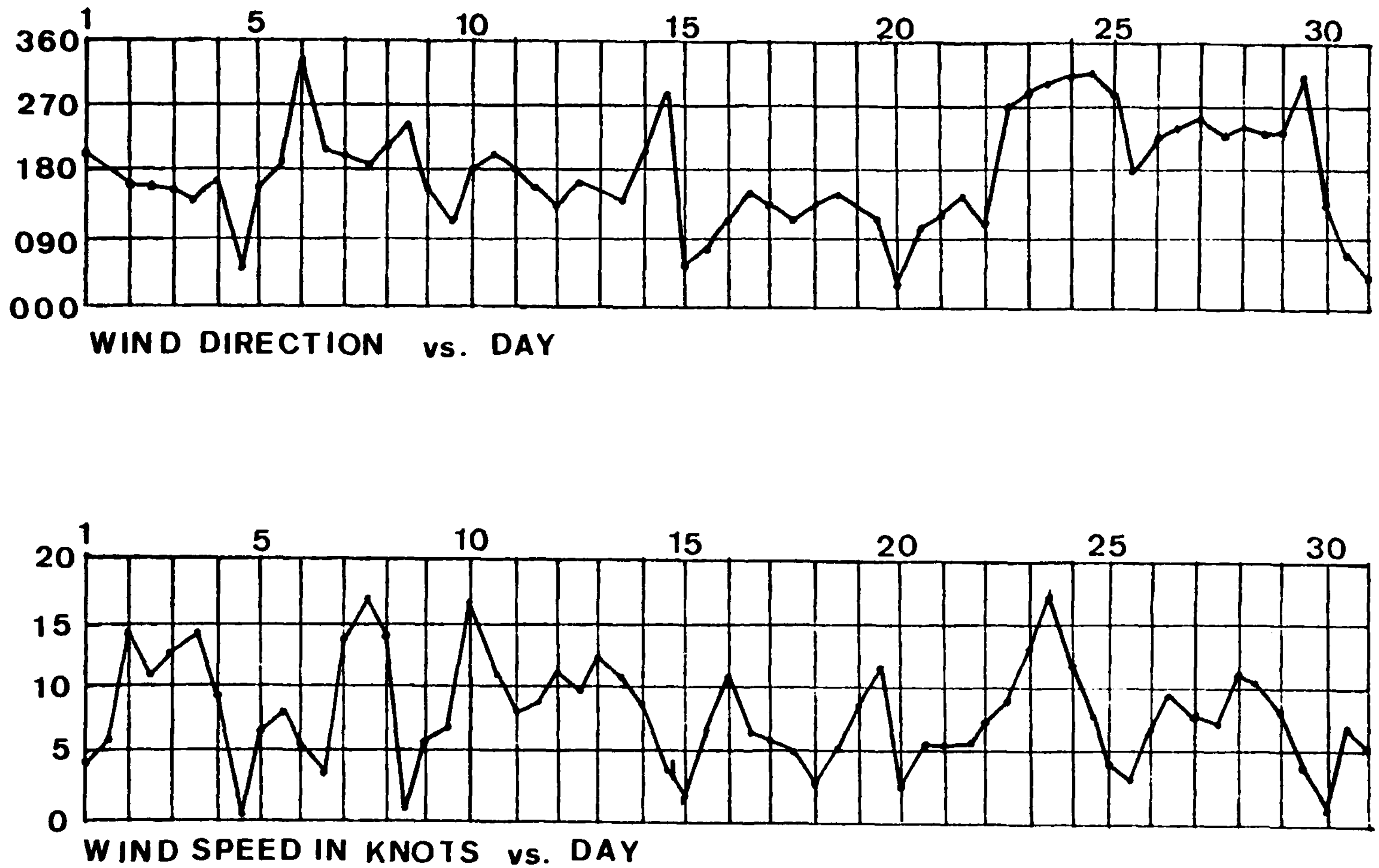


Figure 26. Aug. 1977 Wind Direction and Wind Speed

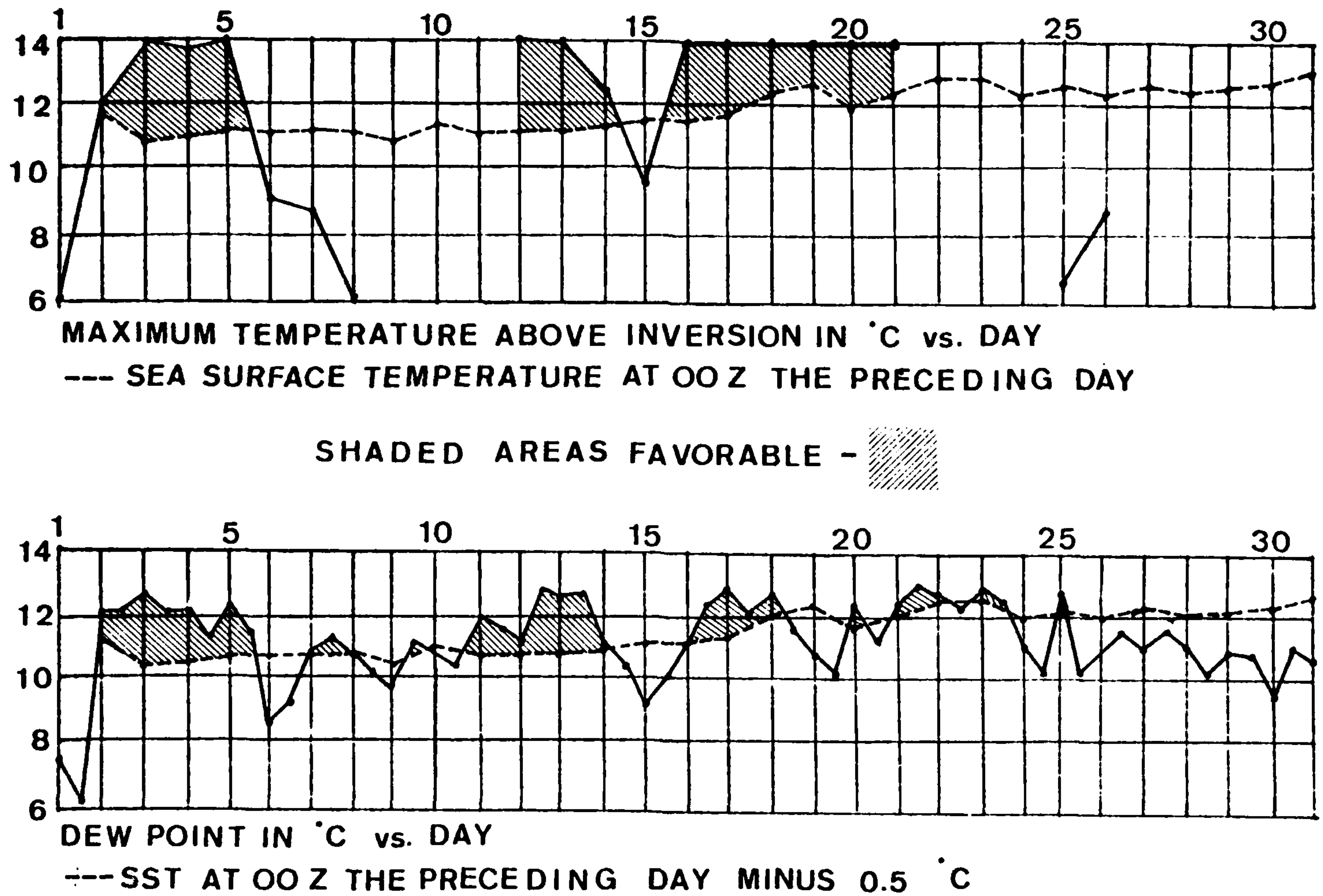


Figure 27. Aug. 1977 Temperature Index and Moisture Index

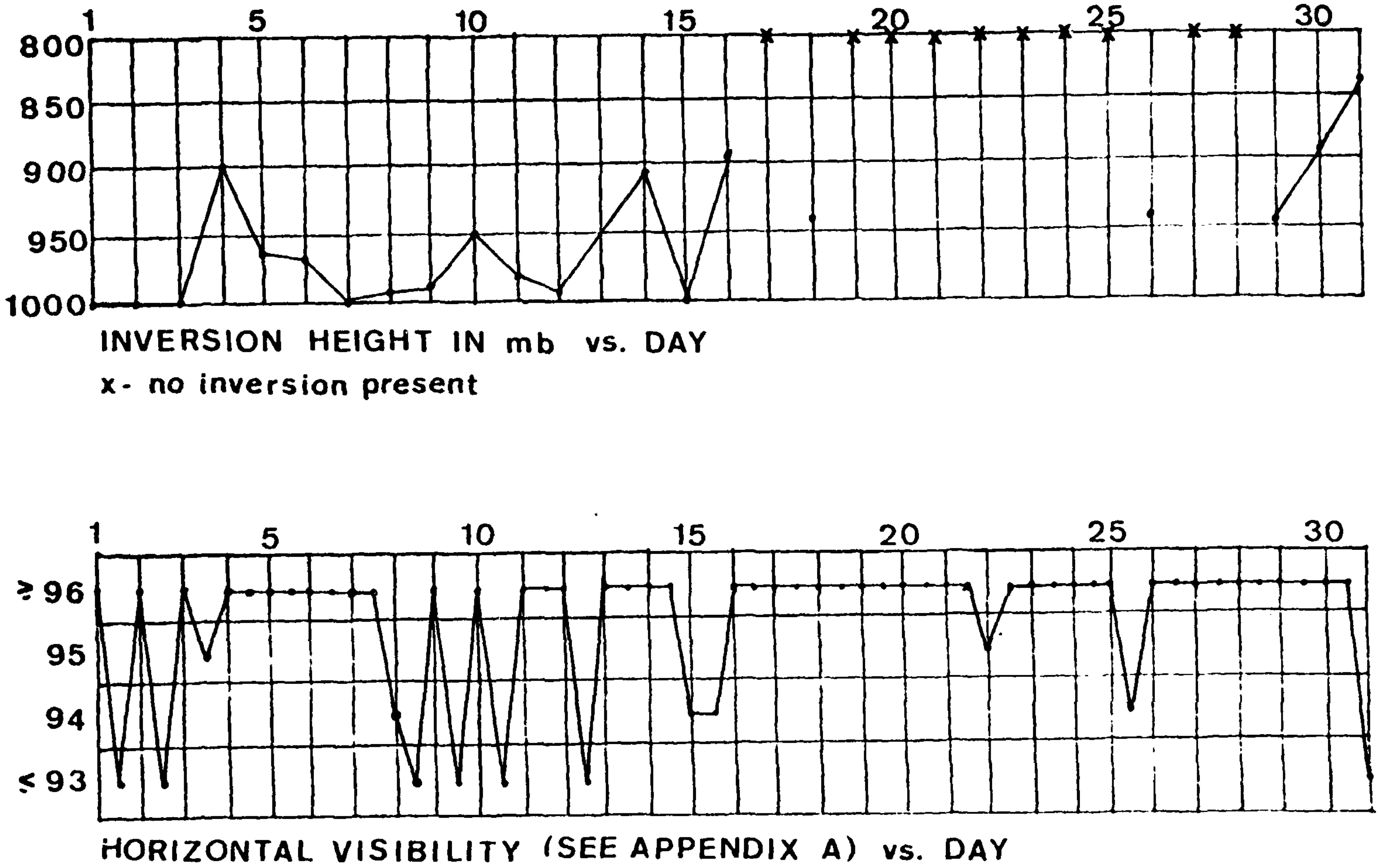


Figure 28. July 1975 Inversion Height and Horizontal Visibility

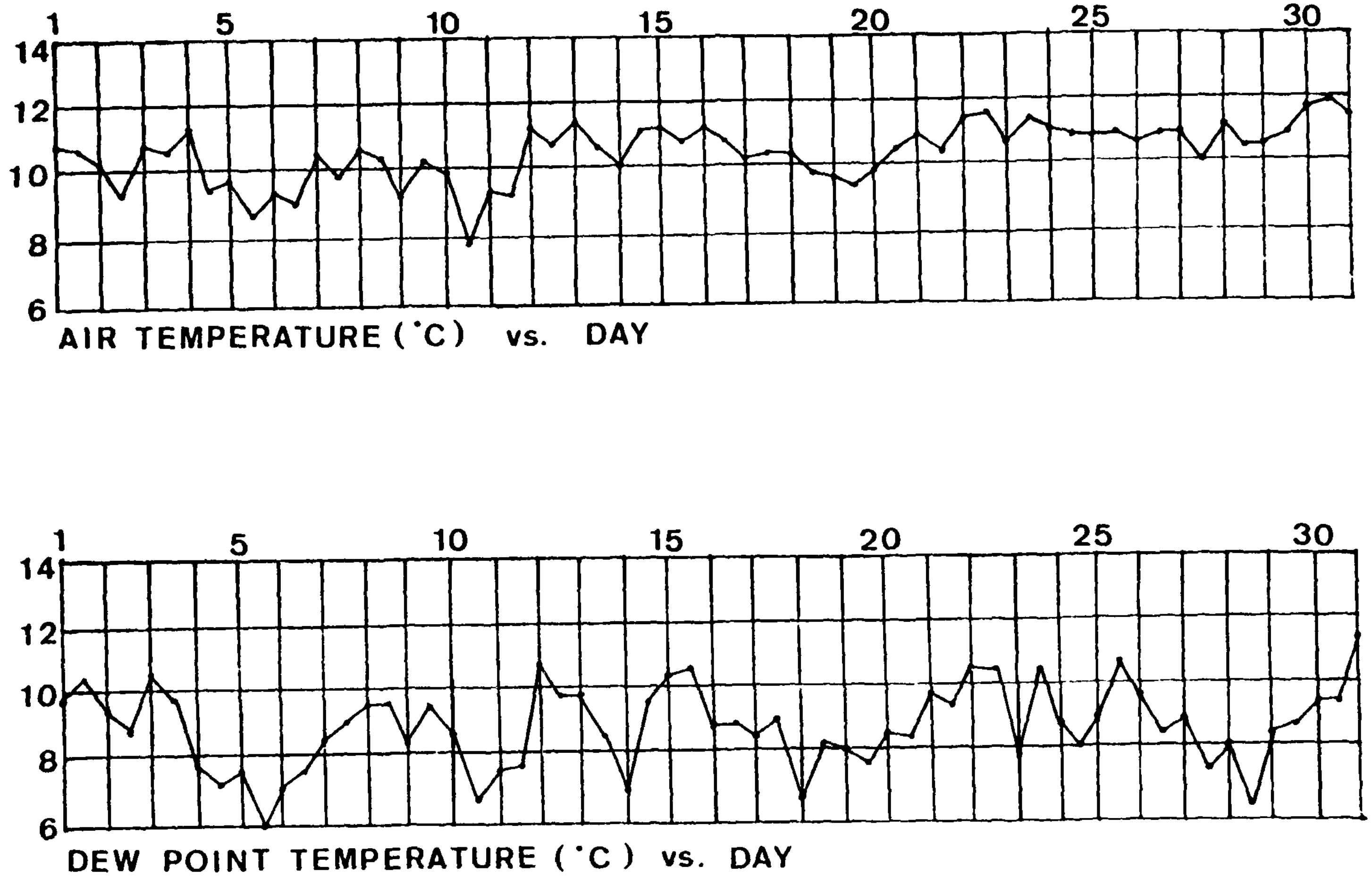


Figure 29. July 1975 Air Temperature and Dew Point Temperature

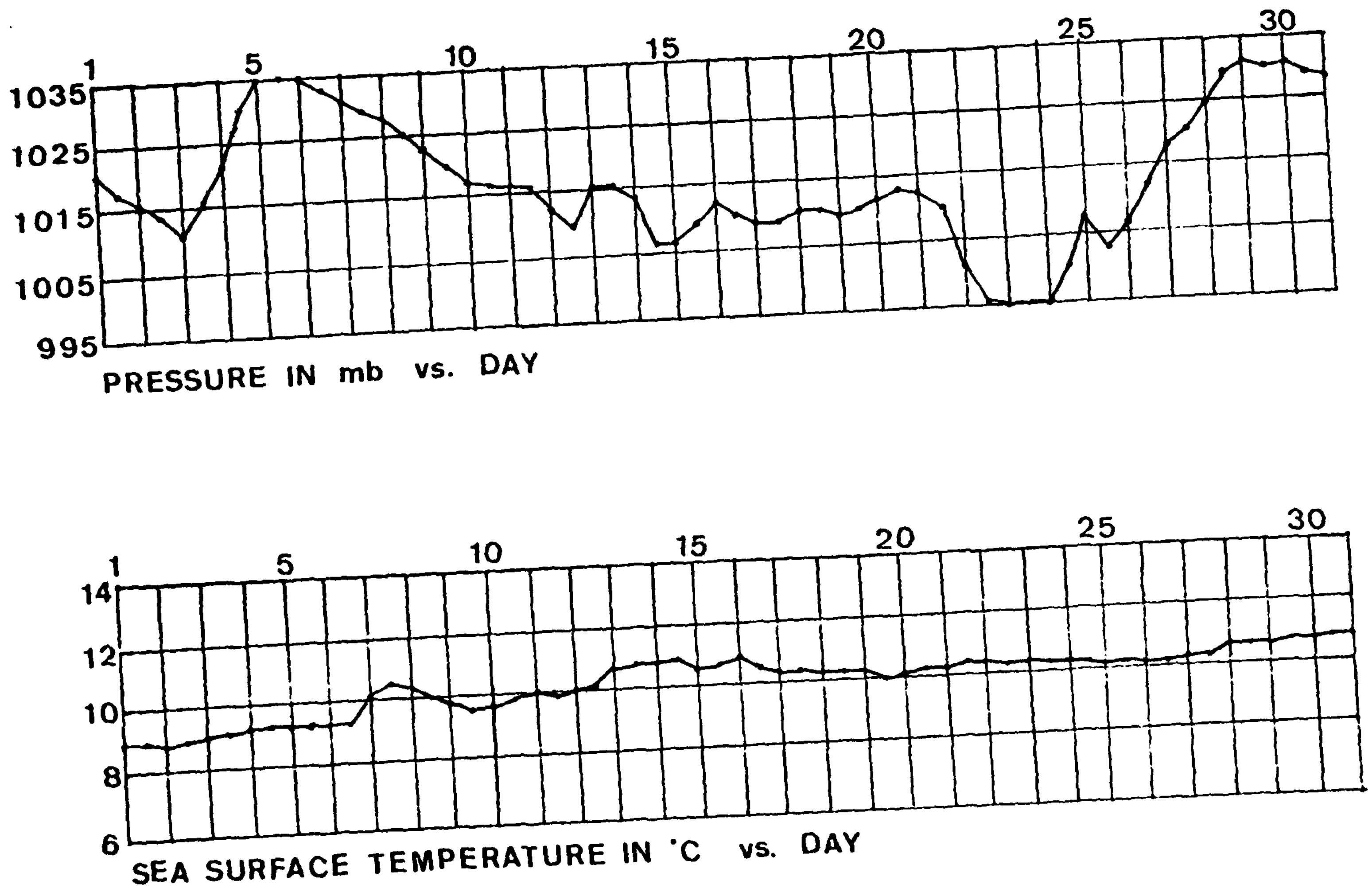
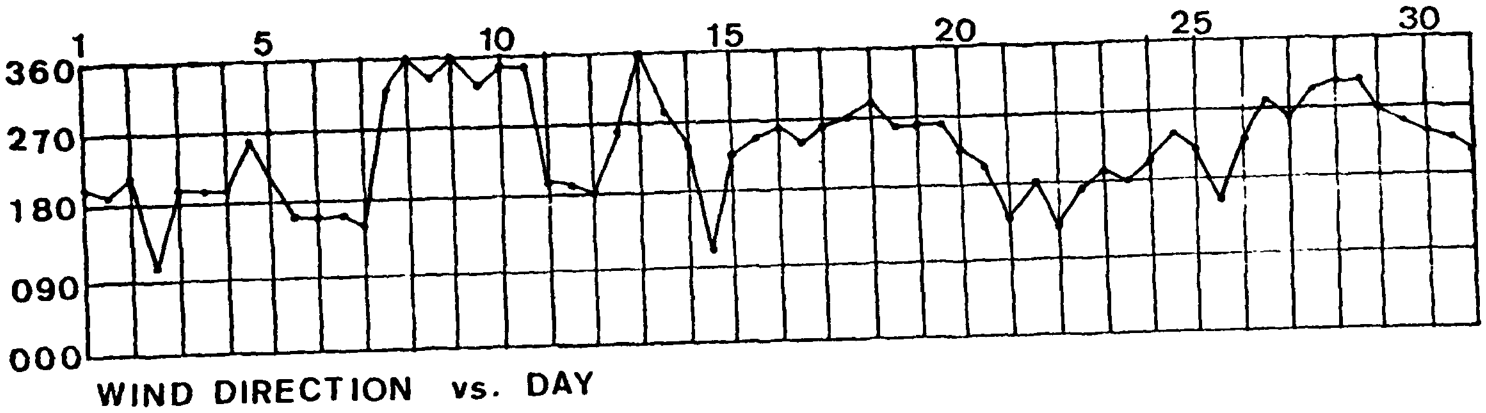


Figure 30. July 1975 Sea Level Pressure and Sea Surface Temperature



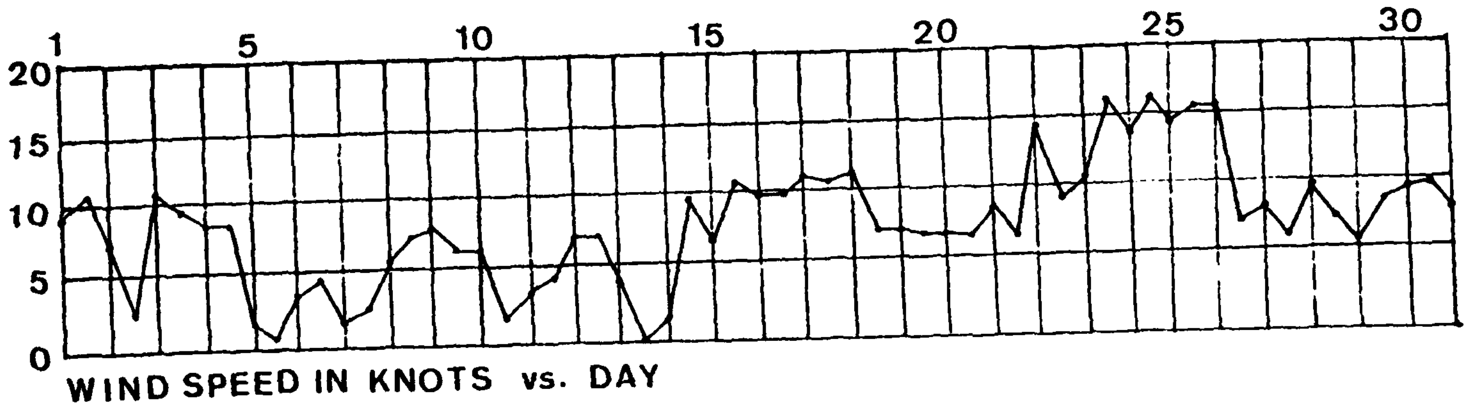


Figure 31. July 1975 Wind Direction and Wind Speed

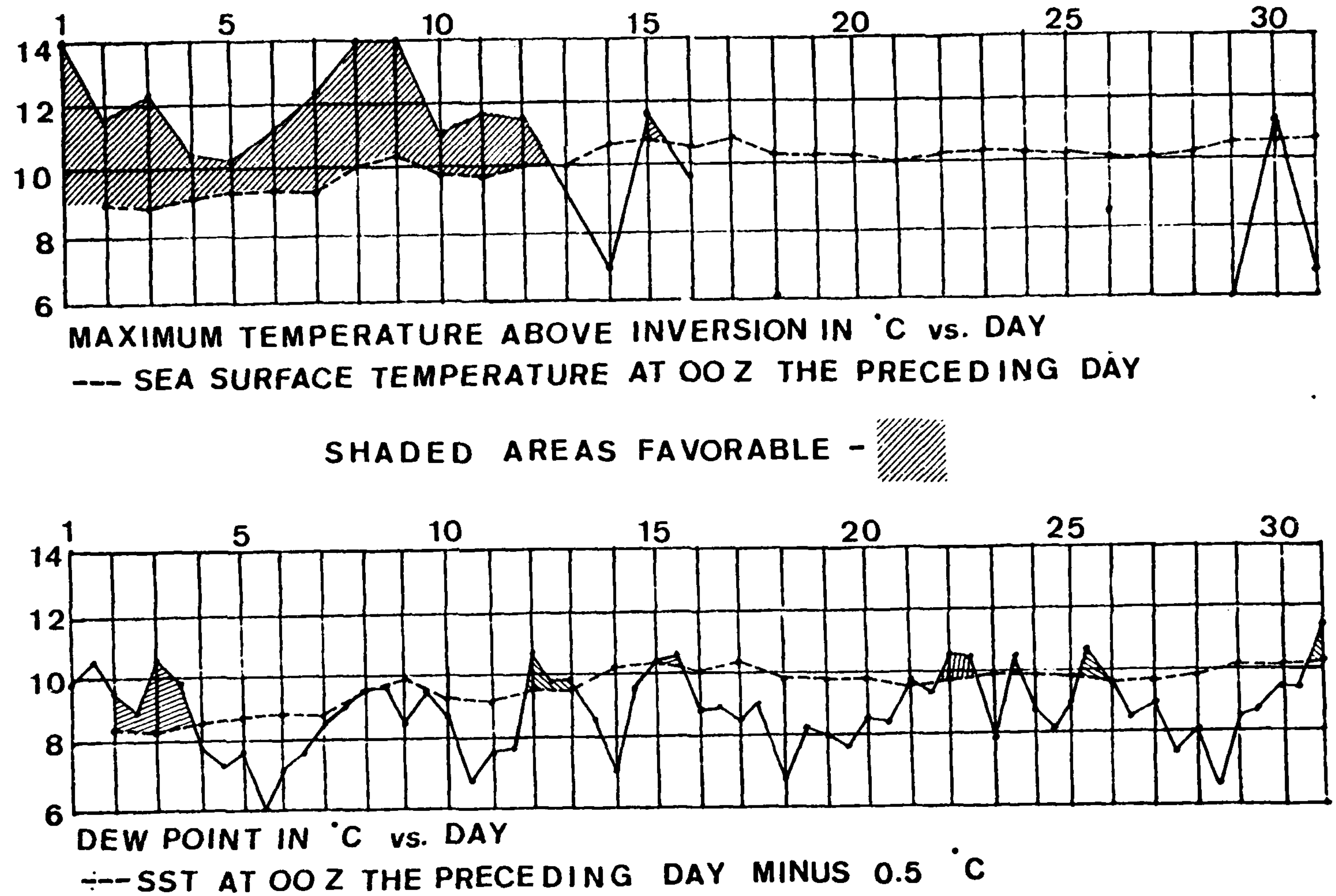


Figure 32. July 1975 Temperature Index and Moisture Index

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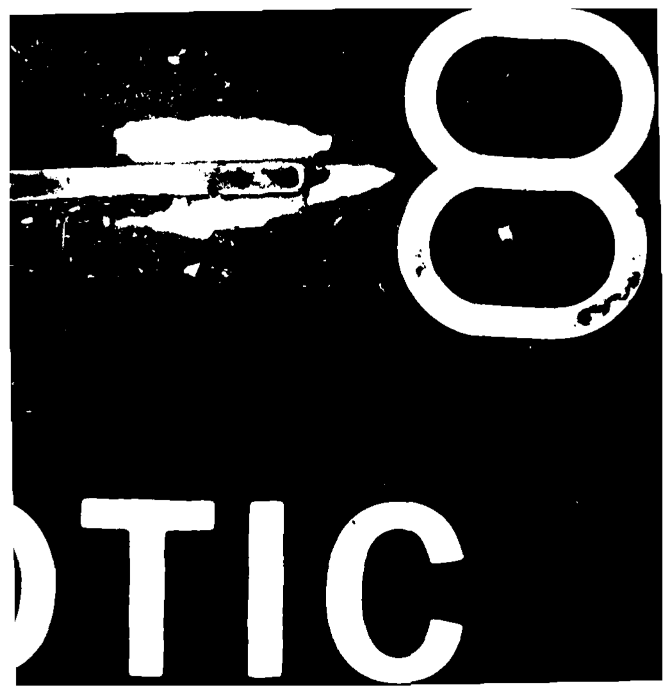
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